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FVCC

PHYSICS OF TECHNOLOGY

COORDINATED BY AMERICAN INSTITUTE OF PHYSICS

THE CAMERA

Optics and Photographic Measurements.

THE CAMERA

THE CAMERA

A Module on Optics and Photographic Measurements

FVCC

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The Camera

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PREFACE TO THE STUDENT

Section A of this module will teach you some of the physics concepts and principles of the camera. The approach will be inductive, descriptive, and non-mathematical. Certain questions will first be raised by your laboratory work; then you will be led to forming some answers to these questions. In Section A, you will not be able to answer all of the questions raised in your lab work. The answers you get will describe what happens, but not when, or how much. To get such *quantitative* answers, you must use numbers, make measurements, and write some equations.

Section B of this module will provide some quantitative answers about physics concepts and principles of the camera. These answers will be formed by what is called an *empirical* approach. In this approach, you make measurements of one quantity for different values of another, all other pertinent quantities being held constant. Then the resulting relationships are said to be empirical.

To discuss why certain answers are or are not correct, we must develop models, or theories, for what we observe. Then we must compare observations with the theory, and we should try to extend the theory to predictions which have not yet been observed. Finally, these new predictions should be tested with experiments. Section C of this module will examine physics theories of the camera, as well as applications of theoretical concepts and principles.

This module has been designed so that you may complete your study of it at the end of Section A, Section B, or Section C. If you already have the skills, knowledge, and understanding taught in Section A, you may begin the module with Section B. The module post-test is divided into three parts, A, B, and C, corresponding to the three module sections.

GOALS FOR SECTION A

The following goals state what you should be able to do after you have completed this section of the module. These goals must be studied carefully, as you proceed through the module, and as you prepare for the post-test. The example which follows each goal is a test item which fits the goal. When you can correctly respond to any item like the one given, you will know that you have met that goal. Answers appear immediately following these goals.

1. *Goals:* Know how the image in a *camera obscura* is affected by changes in aperture size or changes in the distance from the aperture to the screen.

   Item: Suppose that you are viewing the image of a large letter R through a *camera obscura* with a small aperture. The letter is painted on a wall and is upright.

   a. Sketch the image as you would view it.
   b. Sketch the image you would view if the aperture were increased in size.
   c. Sketch the image you would view if the screen were to be moved farther away from a large aperture.

2. *Goal:* Know how the image in a camera having a lens compares with the image in a pinhole camera.

   Item: Suppose that you are viewing a clear, distinct image of the letter R with a pinhole camera apparatus which is modified by placing a converging lens in front of the fully-opened aperture.

   a. How does this image compare with that of part (a) of Item 1 above?
   b. Describe how the image would

change if you moved the screen farther away from the aperture (and therefore farther away from the lens).

3. *Goal:* Know the meaning of chromatic aberration of images produced by lenses.

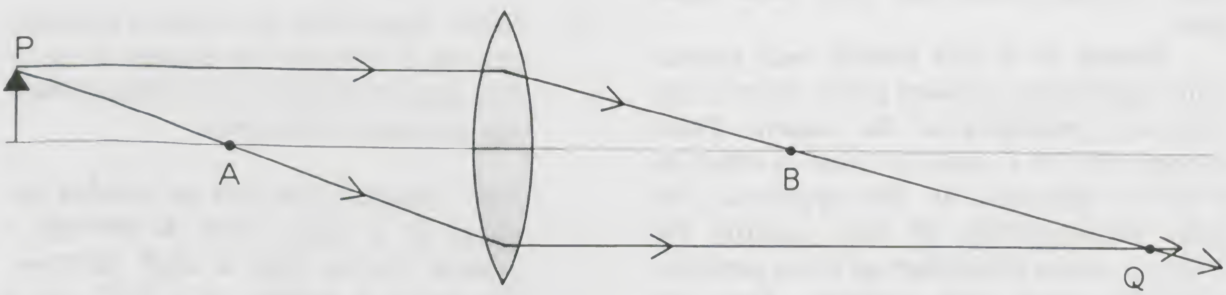
   Item: A converging lens forms a real image of a blue light bulb. If the lens has not been corrected for chromatic aberration,

   a. What happens to the image if the blue bulb is replaced by a red bulb?
   b. Explain how this effect occurs in terms of the bending of light rays by glass.

4. *Goal:* Know the meaning of *focal point, object point,* and *image point* for a converging lens.

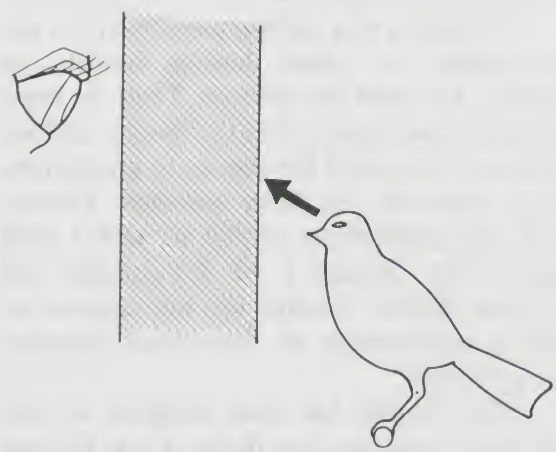
   Item: The figure below shows two light rays travelling from a point, P, on an object to a point, Q, on the other side of a camera lens, where they intersect.

   a. Construct five more rays from point P and show how they pass through the lens and the direction which they then take.
   b. What is the point Q called?
   c. What are points A and B called?



5. *Goal:* Understand the principle of refraction of light rays.

   Item: Suppose that you are looking through a window glass at a bird sitting on a tree limb. The figure opposite shows a cross-sectional view of this situation. Finish drawing the ray of light through the window glass to the eye. Then draw a dashed line back to show where the bird "appears" to be.



Answers to the Items Accompanying the Preceding Goals

1.

(a)

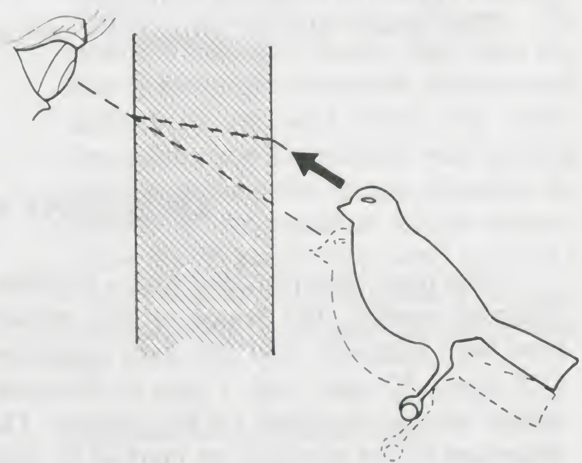
(b)

(c)

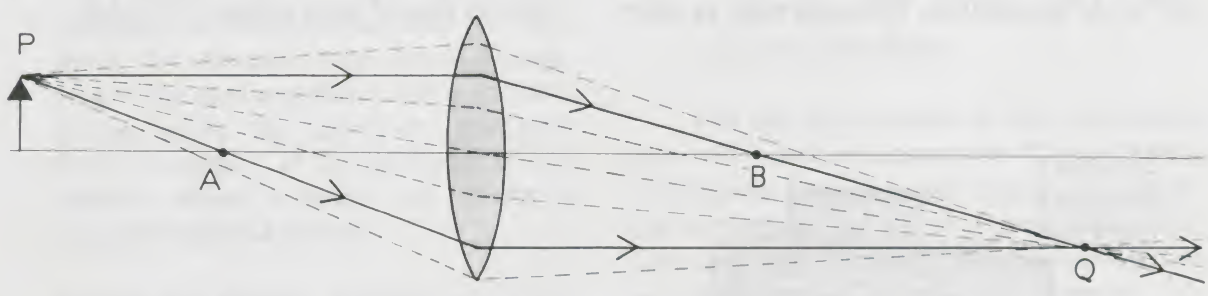
2. a. Brighter.
   b. If it started in focus, it would become fuzzy (out of focus) and larger.

3. a. The image moves farther away from the lens.
   b. Red light is bent less than blue light.

5.



4. a.



   b. Image point.

   c. Focal point.

SECTION A

A Qualitative Approach to the Physics Concepts and Principles of the Camera

THE CAMERA

The word *camera* is Latin. It means "chamber." The fact that we use this word today for the familiar photographic device stems from an earlier gadget called the *camera obscura* (Latin for darkened chamber).

The *camera obscura* produced a replica, called an *image*, of some scene on a screen. An artist could place a sheet of paper on the screen and trace what he saw. If one understands how the *camera obscura* works, it is easy to understand how modern cameras operate.

EXPERIMENT A-1. The Pinhole Camera

You have been provided with a modified Polaroid camera. The lenses of this camera have been removed. You also have 3 pinholes (.25 mm, .50 mm, and 1 mm in diameter) which can be mounted on the camera. The diameters of the pinholes are marked on their mounts.

You should now take out the work sheets for this experiment, which are at the back of the module. Write answers to questions and complete the tables on those sheets as you do the experiment.

Place the camera in a steady position. Place the pinhole with the .25 mm diameter in the holder on the front of the camera (see Figure 1). Extend the bellows by moving the front of the camera as far as possible from the camera back. An object should be placed 20-30 cm in front of the camera and other objects should be at varying distances.

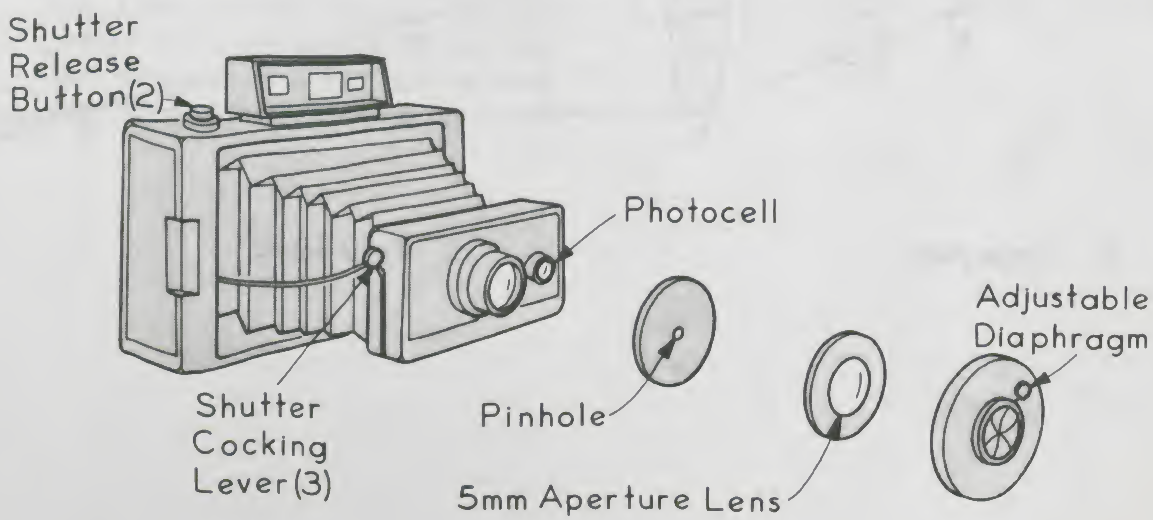


Figure 1.

1. You are now ready to take a picture. The camera should be loaded with Polaroid type 107 black and white film. *Set the film selector to "75."* If you are not familiar with how to do this, see the instructions accompanying the camera. To keep the shutter open for the long exposure time necessary, cover the photocell with the opaque cap. Cock the shutter by pressing the shutter cocking lever (3) down as far as it will go. To make the exposure, depress the shutter release button (2) and hold it down. This will hold the shutter open. At the end of the desired time, close the shutter by releasing the button. To find the correct exposure time, try the first exposure with the shutter open for 1 minute. Develop the film according to the directions and examine the picture. Is the exposure correct? If the picture is too dark, the exposure was not long enough. If it is too light, the exposure was too long. Repeat the above procedure, adjusting the exposure time accordingly, until the exposure is correct.

   Record the pinhole diameter and your best exposure time.

2. Replace the .25 mm pinhole with the .50 mm pinhole. Since you have doubled the diameter of the pinhole, how do you think the exposure time should change to get the best exposure? Make another picture using the exposure time you think is correct. If the exposure is not correct, adjust it until you obtain a properly exposed picture.

   Record the pinhole diameter and your best exposure time.

3. You are now going to double the diameter of the pinhole once again. What do you predict to be the correct exposure time having a 1 mm diameter? Try an exposure at that time. Is it a correct exposure? If not, keep trying.

   Record the pinhole diameter and your best exposure time.

4. Examine the best picture which was taken with each of the pinholes. In terms of the sharpness and clearness of the pictures, which do you think is the best picture? Why?

5. Are objects at all distances from the camera equally sharp in these pictures?

6. Look at your data on diameters and exposure times. Can you draw any conclusions about the relationship between pinhole diameter and exposure time?

7. You have been given a lens with a 5 mm aperture attached to it. Remove the pinhole from the camera and place the lens in front of the shutter. The lens will make your exposure times very short. Open and close the shutter very quickly without moving the camera. Develop the picture. If the exposure is not correct, adjust the exposure time until you get a correct exposure. The exposure time can be shortened by uncovering the photocell.

   Estimate your exposure time.

8. How does this picture compare with your pinhole pictures?

9. In this picture, are objects at all distances equally sharp?

For the next section of this experiment, you will have to remove the film pack from the camera. Since this will expose any remaining pictures in the pack, it is suggested that you use these for additional experimentation before removing them. (For example, you might investigate the effect on the image of changing the distance from the pinhole to the camera back.)

The Camera Obscura

Replace the pinhole with the adjustable diaphragm. Remove the film pack and replace it with the frosted screen. Place a brightly lighted object in front of the camera. With the camera back open, adjust the aperture until it

is nearly its smallest size, open the shutter, and look at the frosted screen. (You may find it helpful to turn off the room lights.)

10. Describe what you see on the screen (The likeness of the object which you see on the screen is called the *image*.)

11. Explain in your own words how you think this image is formed. Observe the image as you move the camera front toward the frosted screen (you will have to press on the piece marked "press to close" in order to do this).

12. How does the image size change as the distance from the hole to the screen changes?

13. How does the brightness of the image change as the distance from the hole to the screen changes?

14. How does the sharpness of the image change as the distance from the hole to the screen changes? (Be careful not to confuse sharpness and brightness.)

15. Move the diaphragm as far as possible from the screen. Watch the image as you open and close the diaphragm.

    How does the image change (size, brightness, sharpness) as the size of the opening changes?

16. Close the diaphragm until it is as small as possible and position it as far as possible from the screen. Observe the screen as the object is moved toward and away from the hole.

    Does the image sharpness change as the distance from the object to the hole changes? If so, how?

In order to make the pinhole camera similar to a lens camera, attach the lens in front of the diaphragm.

17. With the aperture set to the smallest opening, obtain an image.

    How does the image compare with that obtained with the same opening but without a lens?

18. Move the object toward and away from the camera.

    Does the image sharpness change as the distance from the object to the camera changes?

Place the object about one meter from the front of the camera. Adjust the distance from the front of the camera to the screen to give the sharpest image. Open the diaphragm as much as possible.

19. Does the image remain sharp? If the image is not sharp, adjust the distance from the camera front to the screen until you get the sharpest image.

20. How does this image compare with the pinhole image formed with the same opening but without a lens?

21. Move the object toward and away from the camera.

    Does the image sharpness change as the distance from the object to the camera changes?

22. As you change this distance, can you sharpen the image by adjusting the distance from the camera front to the screen?

THE CAMERA OBSCURA

You have seen that something, a simple small hole in one wall of a darkened box, will produce an inverted image on the opposite wall. This discovery was probably a most startling one for early observers. The first *camera obscura* may well have been a room in an ancient Greek or Roman house, shuttered against the bright summer sun, with a chink in the shutter acting as a pinhole. Imagine the astonishment of the inhabitants when they saw their olive trees and the blue Mediterranean sky upside-down on the opposite wall! No one knows exactly when this discovery first took place, but we are sure that the imaging properties were known to Aristotle (384-322 B.C.).

How an Image Is Produced

The pinhole produces an image by eliminating all but a small bundle of light from each point on the object. (Each of these rays is produced by reflection of light by the object.) Figure 2 illustrates this process. Distances and relative sizes have been distorted in this figure.

The light from the *top* of the object will be spread out on the screen in a shape like the pinhole. In this case, that is a small circle, but it could be a square or triangle or any other shape. This circle is the blurred image of the *top* point at the *bottom* of the screen. Light from the *bottom* of the object forms a circle at the *top* of the screen, and this is a blurred image of the bottom of the object. Light from all of the other points on the object make other small circles of light on the screen.

By making the pinhole smaller we let in less light. This makes the image more distinct by reducing the size of these tiny circles on the screen. The effect of a smaller pinhole is illustrated in Figure 3. The large circles of light at the left in Figure 3 produce more light on the screen. Because of the size of these circles, and because they overlap with other circles, the image will be blurred. The right side of Figure 3 shows much smaller circles. For this smaller pinhole, there would be a dimmer image, but its sharpness would be increased because there is less overlapping of circles.

The Effect of a Lens

In Experiment A-1, you observed that a lens in front of the pinhole had the effect of sharpening the image, even when using the larger pinholes. Figure 4 shows this effect. The lens converges the light beam to reduce

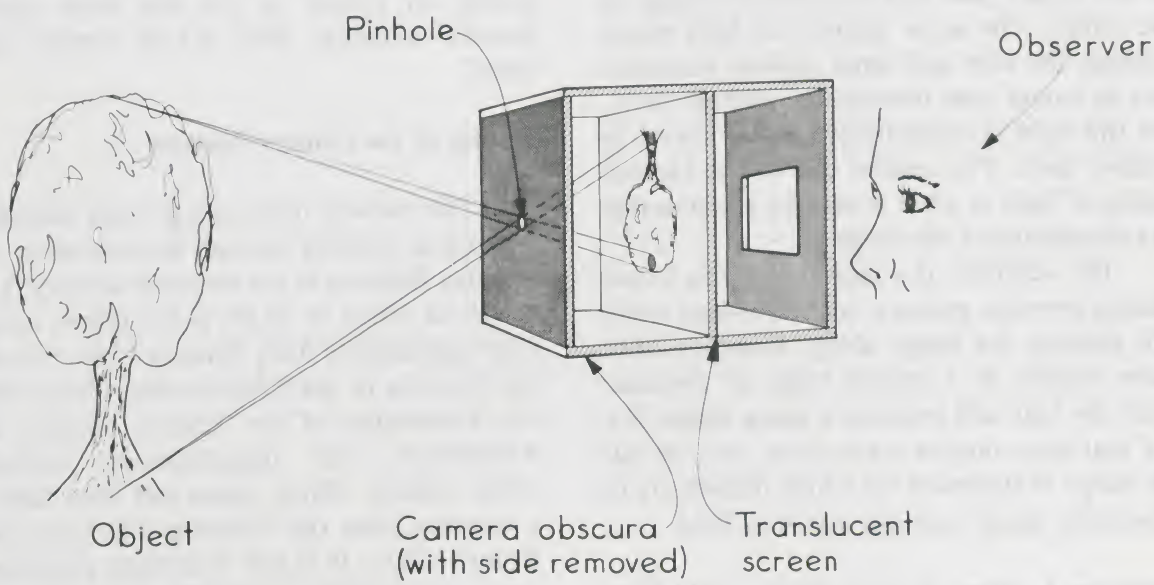


Figure 2.

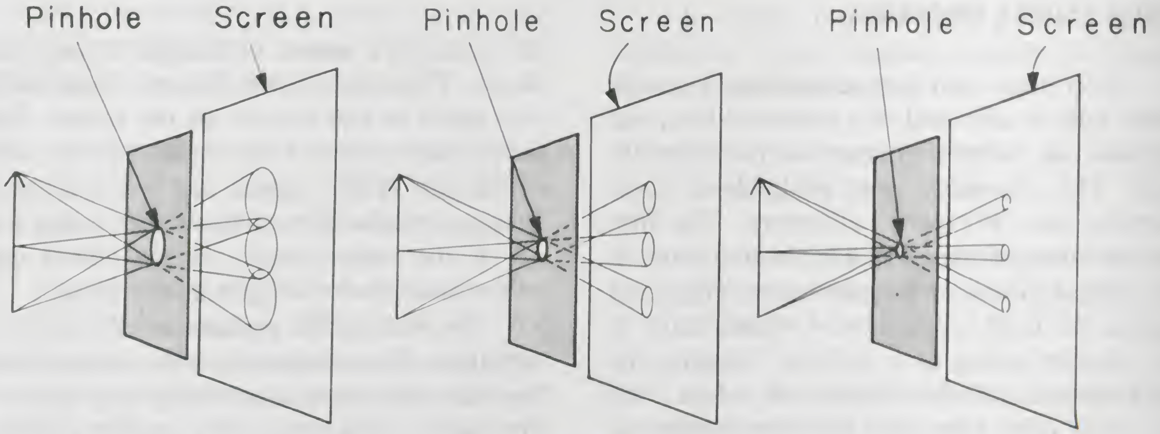


Figure 3.

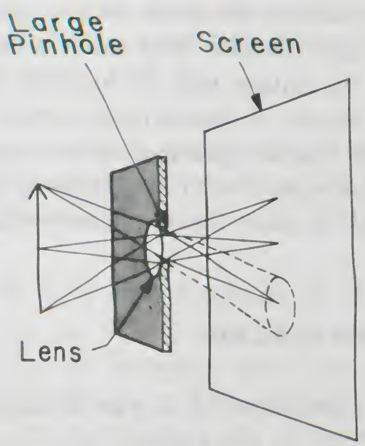


Figure 4.

the spot of light on the screen from a point on the object, and this sharpens the image on the screen. The same amount of light passes through the lens and large pinhole combination as would pass through the pinhole alone, but this light is concentrated in the screen in smaller spots. The smaller size of the blurred circles of light is what is seen by the observer as a sharpening of the image.

The addition of a lens allows you to use a larger opening, giving a brighter image, while still keeping the image sharp. However, only those objects in a certain range of distance from the lens will produce a sharp image. We say that these objects are *in focus*, and we call the range of distances for which objects are in reasonably good focus the *depth of field*.

Question 1. What do you think would happen to the image produced by a pinhole camera if the pinhole were square? Try making such a pinhole camera. Do your observations confirm your predictions?

Question 2. How can the camera obscura image be made larger? What else happens to the image when it is made larger?

Question 3. What would you see in a camera obscura with two pinholes on the same wall? Try making such a set of pinholes. What do you observe?

Question 4. In the deep shade of a tree on a sunny summer day, one can see small circles of light on the ground. Aristotle observed that during an eclipse of the sun these circles became crescents. Why did he observe crescents?

History of the Camera Obscura

The *camera obscura* has been described by various authors through the centuries: the Arabian Alhazen in the eleventh century; Leonardo da Vinci in 1519; and a fellow named Giovanni Battiste della Porta in 1558. (He was the first one to use it for drawing.) From then on, knowledge of the camera obscura was widespread, and improvements followed rather rapidly. Since lenses had been used as a burning glass (by focusing the sun) since Roman times, it is not surprising that lenses were soon combined with the camera obscura to give a brighter image. By 1589, della Porta

described this improvement. In fact, he invited some friends in for a show and hired actors to put on a little play outside. The sight of little people moving upside down on a wall startled and frightened his friends. It wasn't long before della Porta was facing a Papal Court on a charge of sorcery. (He was acquitted.)

By the middle of the next century, Scientists had realized that the artist did not need to be inside the camera, but rather could look from the outside at a translucent screen. The brighter image from improved lenses probably made this advance possible. After that, cameras could become truly portable. Figure 5 shows a portable *camera obscura* which used a mirror to project an image. This is much like those used from the seventeenth to the nineteenth century.

Question 5. When a lens is used as a burning glass, is it forming an image? If so, of what?

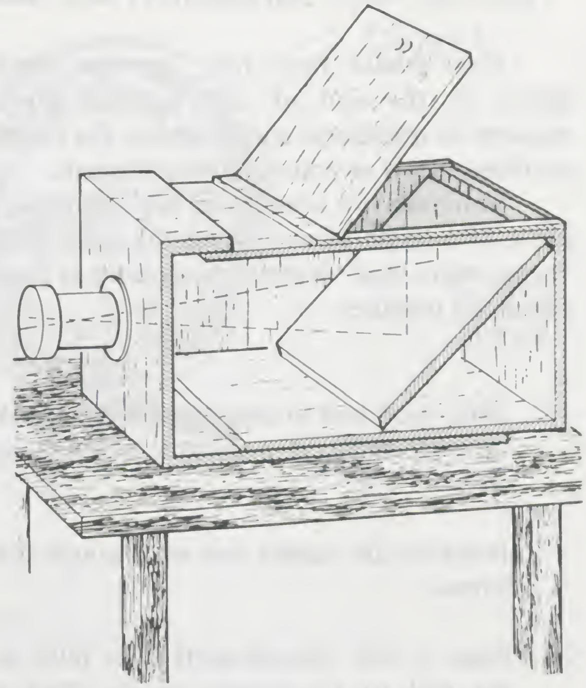


Figure 5.

EXPERIMENT A-2. Observations of Lenses; Refraction

You should now take out the work sheets at the end of this module. Write answers to questions, and complete the tables on those sheets as you do the experiment.

You have two lenses: one is a "thin lens" made of a single piece of glass; the other is an "achromatic lens" made of two pieces of glass cemented together.

1. Hold each lens at arm's length and look through them at a distant, well-lighted area.

   Describe the images you see through the lenses.

2. Place a clear incandescent light bulb at the end of an optical bench. Place a white screen on the bench 1 m from the bulb. Put the "thin lens" between the bulb and the screen on the bench. Move the lens back and forth to obtain an image of the filament of the bulb on the screen.

   Describe the image seen on the screen.

3. Move the screen slightly closer to and then slightly farther from the light bulb. Observe the colors seen at the edge of the image.

   What color do you see when the screen is moved closer to the light bulb?

4. What color do you see when the screen is moved farther from the light bulb?

5. Replace the thin lens by an achromatic lens and follow the same procedure you used with the thin lens.

   Do you observe the same color effects?

6. Use the thin lens again, and position it to obtain the best image you can get. Using a hole cut in a piece of cardboard, cover the outer half of the radius of the lens. Move the screen until the sharpest image is formed.

   What is the lens to screen distance?

7. Now remove the ring of cardboard and cover the center half of the lens. This can be done by taping a coin to the lens with clear tape. Move the screen until the sharpest image is formed.

   What is the lens to screen distance?

8. Are the distances in steps 6 and 7 the same?

Refraction

We will now observe the behavior of narrow beams of light (called *light rays*) as they pass through transparent materials. You have been provided with a ray tracing device. (The device may be a Hartl optical disc, as shown in Figure 6, or similar equipment.) Direct the light source at a distant screen. (For example, a far wall in the lab.) Focus the beam so that a clear image of the filament appears on the screen. Now move the source so that the light falls on the slits of the optical disc. Several parallel rays of light should then enter the apparatus, as indicated in Figure 6. Adjust the disc so that lines of light are visible on the back surface all the way across the disc. Position a piece of glass shaped like a semicircle as shown in Figure 6, so that the rays enter the glass perpendicular to the flat surface. Block all slits, but the center one, so that a single ray of light strikes the semicircular glass plate at the center of the flat base. When the ray strikes the base perpendicularly and passes through the glass plate without bending, everything is properly adjusted. When a ray strikes a surface perpendicularly, we say that the ray is *normal* to the surface. Rotate the glass plate, keeping the ray striking the midpoint of the base, and observe the ray as it emerges.

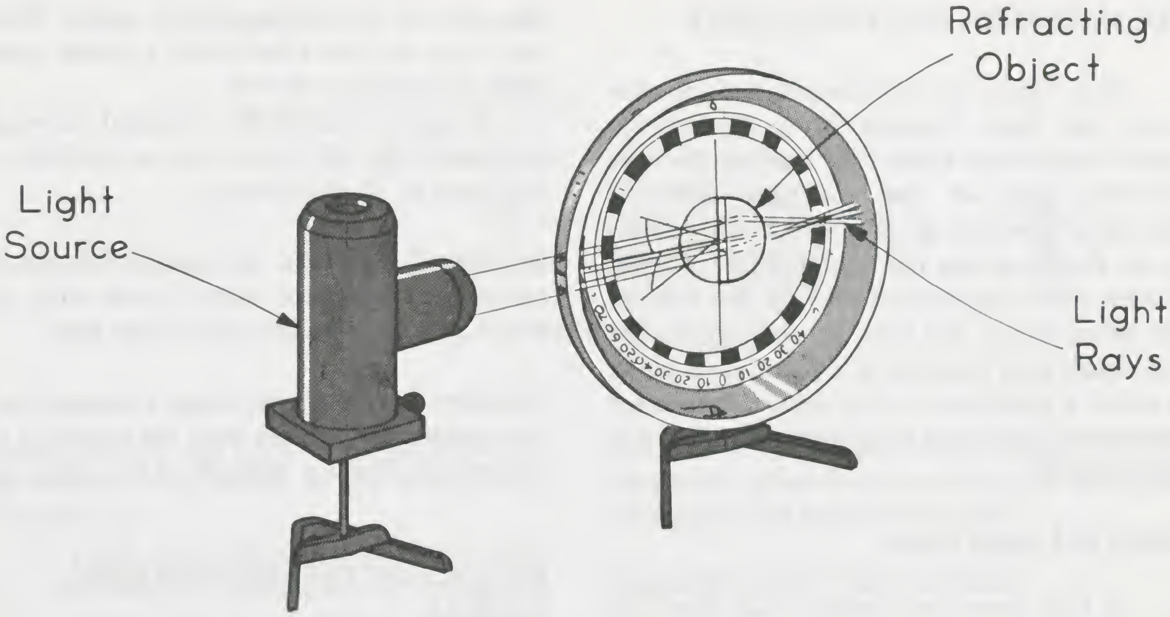


Figure 6.

9. Is the angle the incoming ray makes with the normal (perpendicular line) to the base larger or smaller than the angle the emerging ray makes with the same normal?

10. Why do you suppose there is no bending of the light ray at the curved surface of the glass plate?

11. If you increase the size of the angle the incoming ray makes with the normal, what is the effect on the angle the emerging ray makes with the normal?

12. Turn the glass plate around so that the ray strikes the circular edge and passes from the glass to air at the midpoint of the base.

    Does the angle the ray makes with the normal increase or decrease as it passes from the glass lens to air?

13. Unblock enough slits to produce five parallel rays of light. Place the glass which is shaped like the cross-section of a lens into the apparatus.

    Sketch what happens to the rays as they pass through the "lens."

FOCAL LENGTH AND FOCAL POINT

The "lens" in Experiment A-2 concentrates the light, bending it by the process called *refraction.* Light rays passing through different parts of the lens bend different amounts; however, all rays which are parallel to the axis bend just the right amount to cross at one point (approximately) on the axis on the other side of the lens. Figure 7 shows the way these rays intersect at a point. This point is called a *focal point* of the lens; the distance from the lens to the focal point is called the *focal length.*

Object and Image Points

A lens forms one point of an image by bending all the light rays which reach the lens from a single point on the object so that these rays meet again at a single point on the other side of the lens. As shown in Figure 8, the latter point is the image of the former.

Question 6. For an object like a tree or a winter scene, where does the light which leaves an object point originate? (Are these light rays different from those coming from a light bulb?)

The rays continue through the image point so the image can be viewed *directly,* without a screen, if the observer's eye is in line to intercept the rays after they go through the image. A screen aids in viewing the image by reflecting the light in a way which scatters the rays from the image so that they can be viewed from other angles. This is why you can see what is on a movie screen from any seat in a theater.

Figures 7 and 8 are idealized drawings; real lenses do not focus rays as perfectly as suggested by these drawings.

Question 7. Is a light ray passing through the center of a lens bent more or less than one which goes through the edge of the lens?

Question 8. Is the blue image produced by a lens closer to or farther from the lens than the red image? Draw a diagram of this situation.

HISTORY OF THE PHOTOGRAPHIC CAMERA

Because of imperfect focusing, lenses did not at first solve all the problems of forming sharp images, especially as the aperture of a camera was opened up to let in more light. Much work remained to be done before modern photographic lenses were developed. With the *camera obscura* a dim image was not a great problem because the human eye is a sensitive light detector. However, by the early 1800's, a number of investigators were already experimenting with putting light-sensitive materials in place of the viewing screen to record the image. In other words, they were trying to let the light draw its own picture.

In 1826, Niepce coated a sheet of pewter with an asphalt solution, inserted it into a

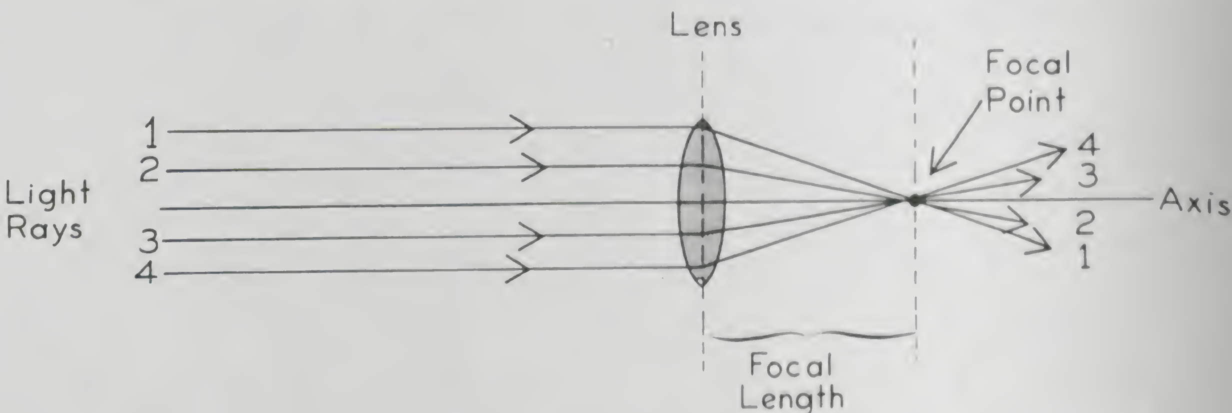


Figure 7.

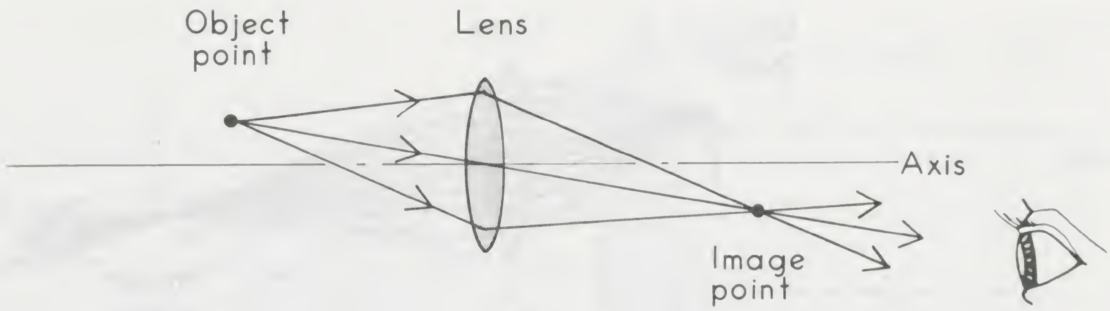


Figure 8.

camera obscura, and after an 8 hour exposure had a dim, fuzzy image of his farmyard in central France.

In 1839, Louis Daguerre, a French artist and experimenter, announced to the world that he had invented a method of making permanent images. The photographic camera had been born. Daguerre's original camera is shown in Figure 9.

With these early processes, one great problem was that a very long exposure time was needed to get an image on the light sensitive plate or paper. Better lenses could help because they produced sharp images even with large apertures which let in more light. From 1839 until the present, there have been constant improvements in lens design and film sensitivity which have permitted the recording of images with less and less light.

PRINCIPLES OF THE CAMERA

The camera as we know it can still be thought of in its most elementary form: It is a darkened chamber with a lens which forms an image on a light-sensitive film. The image is formed when the lens converges light rays coming from the object. Every light ray from a point on the object which passes through the lens is bent so that each goes through the corresponding point in the image, as shown in Figure 10.

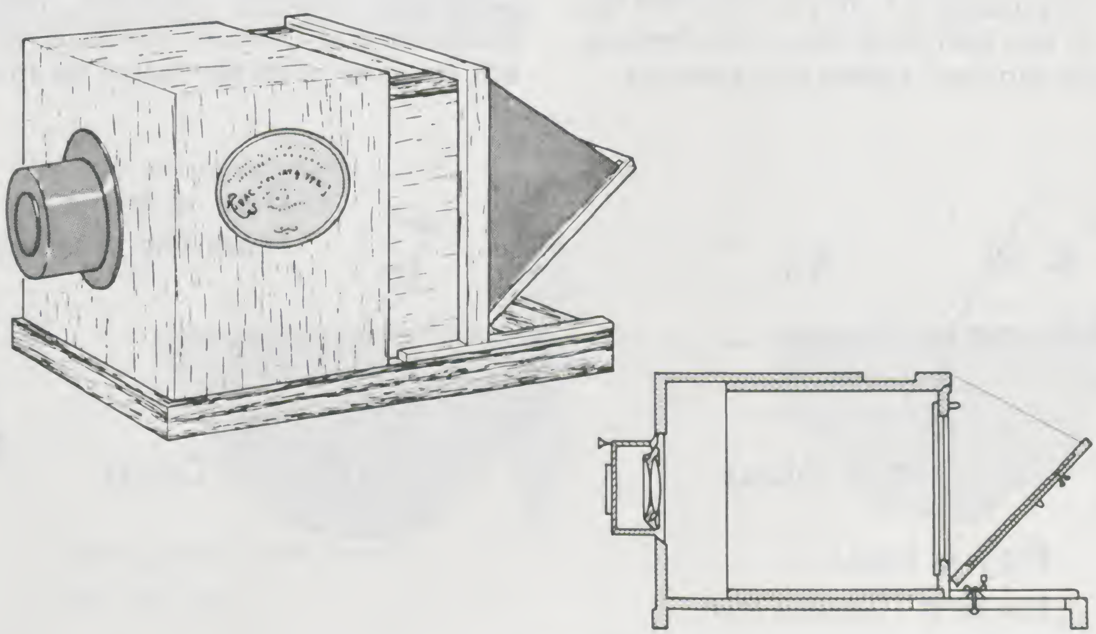


Figure 9.

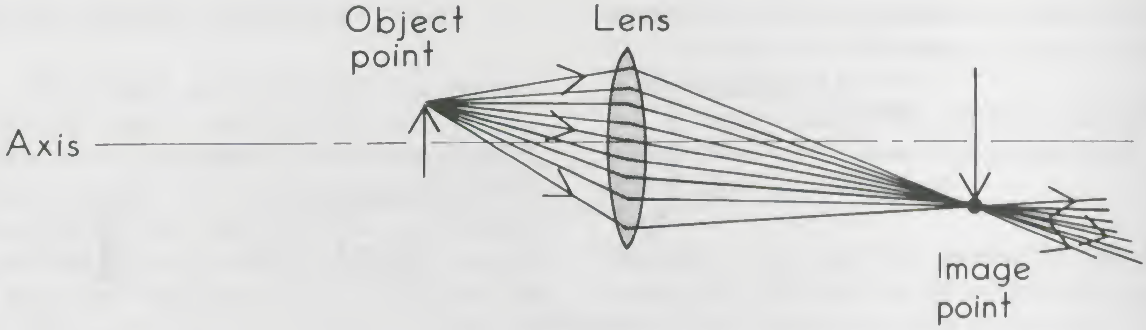


Figure 10.

Refraction and Lenses

The focusing produced by lenses depends upon the bending of light that occurs at lens surfaces. You have learned that when light crosses the boundary between two different materials, such as air and glass, the light bends at the surface. This bending is called *refraction.* When light travels from air into glass, the refracted ray bends *toward* the normal, and when light travels from glass into air, the refracted ray bends *away from* the normal. This behavior is illustrated in Figure 11, and it demonstrates the fact that the light path can be reversed. (That is, light travels along the same path in *either* direction.)

Question 9. From your experience with lenses in Experiment A-1, do you think that red light or blue light bends more when traveling from air into glass? Explain your reasoning.

Lens Aberrations

You have learned that lenses do not produce perfect images. Rays which pass through the outer portion of the lens produce an image at a slightly different place than do those passing through the inner portion. This effect is called *spherical aberration.* Also, different colors of light from the same object produce images at slightly different points. This effect is called *chromatic aberration.* These aberrations are illustrated in Figures 12 and 13. The effects are greatly exaggerated in the figures compared to what would actually be observed.

Notice in Figure 13 that the red part of the arrow is focused further away from the lens than is the blue part. This effect is called *longitudinal chromatic aberration.* There is another kind of chromatic aberration. Notice that the image of the blue half of the arrow is

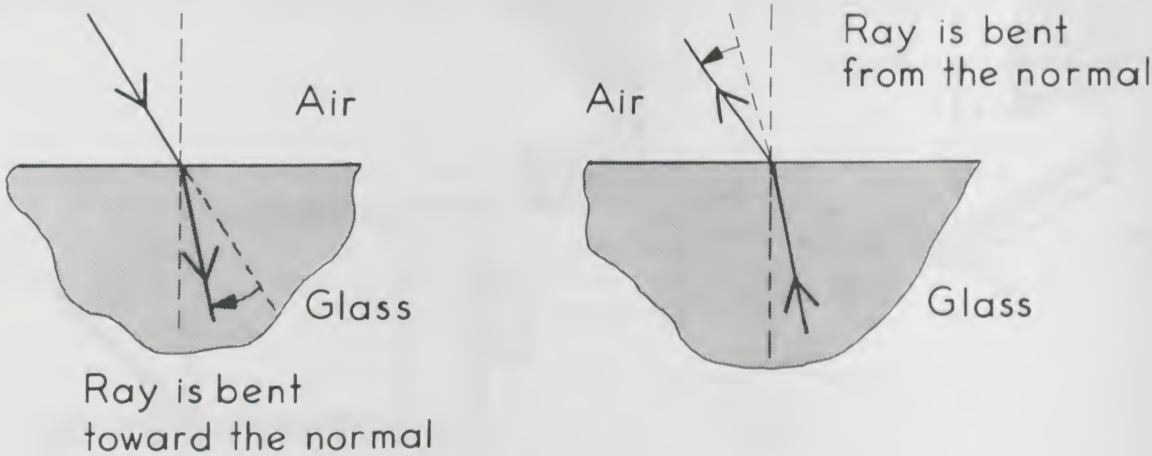


Figure 11.

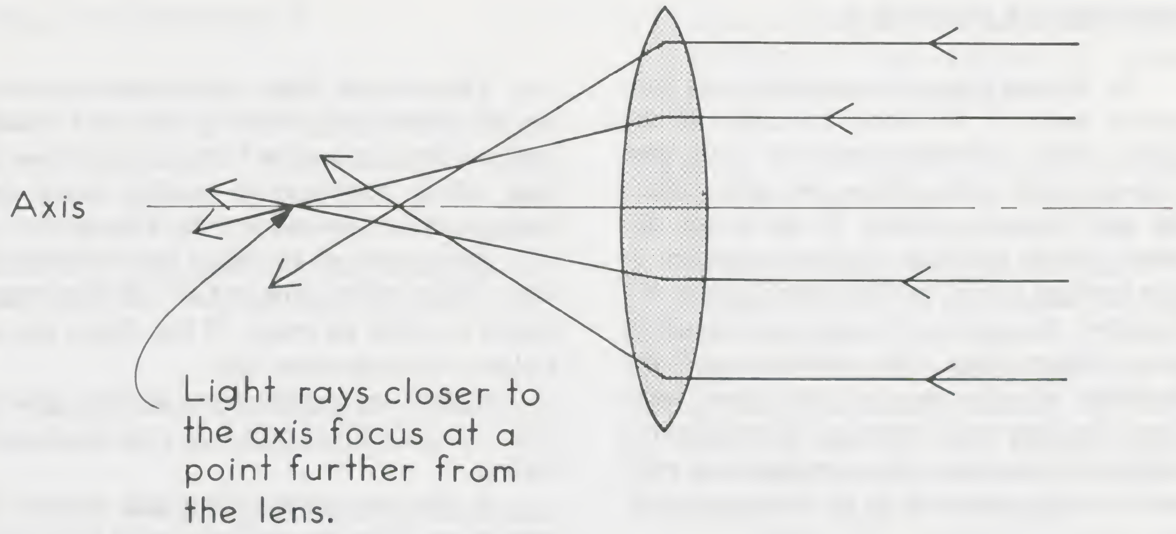


Figure 12.

shorter than the image of the red half. This is called *lateral chromatic aberration.*

Achromatic Lenses

You have already seen that chromatic aberration can be corrected by using what we have called an *achromatic lens.* Chromatic aberration occurs because a simple lens bends some colors of light more than other colors (blue light more than red light). The kinds of lenses you have used converge parallel rays of light; therefore, they are called *converging lenses.* Other lenses, which are thinner in the middle than at the outer edges, cause parallel rays to diverge (spread out). Such lenses are called *diverging lenses.* When a diverging lens of the right shape and material is bonded to a converging lens of another material, this combination can be made to converge all colors almost the same amount. Such a combination is an example of what is called an *achromatic lens.*

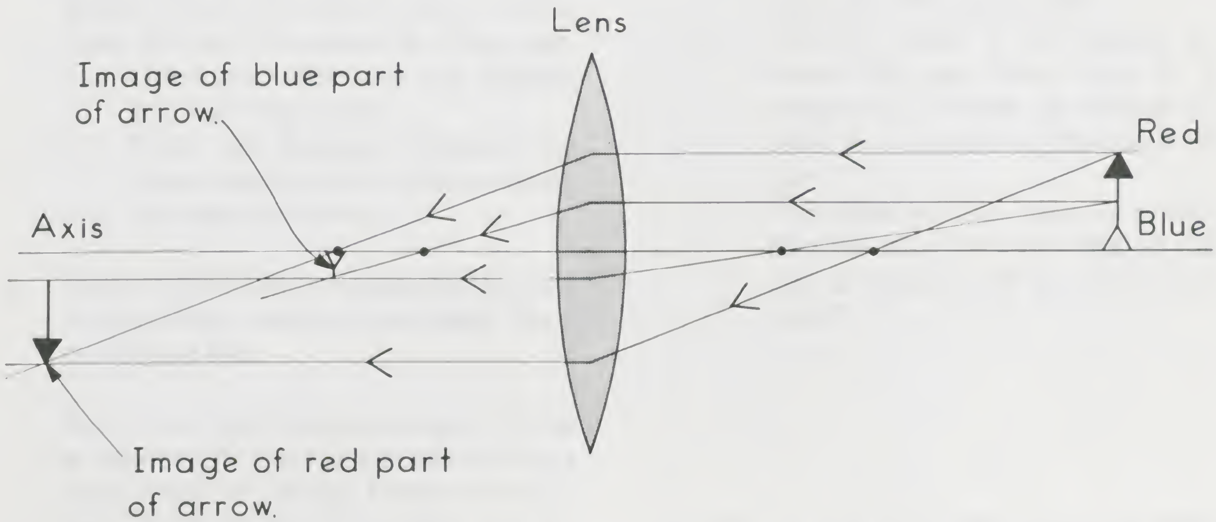


Figure 13.

SUMMARY OF SECTION A

In this section of the module, you have learned some of the basic principles of the camera. These principles have been in the area of geometrical optics. There are other principles and concepts which we have not discussed. Some concepts will be examined in later sections of the module; they include the f number, the power of a lens, and exposure times. Others, like ASA numbers and the chemistry of photography, you must learn about through other sources. The following statements summarize the concepts and principles you have learned so far in this module.

An object is *in focus* when its image, produced by a pinhole or converging lens, is sharp and distinct.

The range of distances from the lens of an object for which its image is in focus is called *depth of field.*

Refraction is the bending of light rays at the boundary between two different transparent materials.

Rays of light which are parallel to the axis of a thin converging lens are converged to a point on the other side of the lens. This point is called a *focal point.*

The distance from a thin converging lens to a focal point is the *focal length* of a lens.

The cone of light, which leaves a point on an object (an *object point*) and which strikes a lens, is bent to form another cone of light which converges to another point (an *image point*) on the other side of the lens.

Each point on an object has a corresponding image point. The set of all the image points is called an *image.* If the object lies in a plane, the image does also.

A light ray passing from air into glass is bent *toward* the normal to the boundary surface.

A light ray passing from glass into air is bent *away from* the normal to the boundary surface.

The fact that different colored images focused from the same object are focused at different positions is called *chromatic aberration.*

Chromatic aberration is a result of the fact that different colors of light are bent by slightly different amounts when they pass between air and glass.

Rays of light which are parallel to the axis of a spherical lens are bent a greater amount when they pass through the lens near its edges than those which pass through the lens near its center. This produces *spherical aberration.*

GOALS FOR SECTION B

The following goals state what you should be able to do after you have completed this section of the module. The example which follows each goal is a test item which fits the goal. When you can correctly respond to any item like the one given, you will know that you have met that goal.

1. *Goal:* Know the meaning of the *focal length* of a thin converging lens.

   Item: Describe precisely how you would find the focal length of a thin converging lens.

2. *Goal:* Without an equation, know how the image location and image height are related to object position for a converging lens.

   Item: Suppose that you have formed the image of an object using a converging lens. Describe what happens to the image position and height as the object is moved away from the lens.

3. *Goal:* Know how to construct a principal ray diagram for a converging lens.

   Item: For a converging lens of focal length 20 cm, an object is placed 60 cm from the lens. The object is 10 cm high.
   a. Construct a principal ray diagram and locate the image.
   b. From the diagram, determine the image height and the distance from the image to the lens.

4. *Goal:* Recall and use equations for predicting image position and height for a converging lens.

   Item: An object having a height of 6 cm is located 35 cm from a lens having a focal length of 10 cm. Using equations, find the position of the image and the image height.

5. *Goal:* Understand the quantitative relationship of image position to object position for a converging lens.

   Item: A converging lens has an object located at a distance x_1 from the focal point (in a direction away from the lens). For this position of the object, the image is located 16 cm beyond the focal point on the other side of the lens. Suppose that we replace this lens by another lens having one-half the focal length of the first lens. Then we adjust the object position so that it is again a distance x_1 from the focal point.
   a. Which way must we move the object to make this adjustment?
   b. Calculate the value of the new image distance.

6. *Goal:* Be able to apply the two principles of lenses learned in this section of the module to the camera.

   Item: Suppose that you are designing a camera using a converging lens with a focal length of 80 mm. The design specifications require that the camera focus on objects from as close as 3.0 feet (91 cm) from the film plane out to infinity.
   a. What width (minimum distance from lens to film plane) will you select for the camera case?
   b. How far must it be possible to move the lens from when it is focused on objects at infinity to when it is focused on objects at 3.0 feet.
   c. How high will the image be on the film for a tree 40 feet high (1220 cm) or which is 200 feet (6100 cm) away?

(Answers to the items accompanying these goals appear on page 20.)

SECTION B

An Empirical Approach to the Optical Concepts and Principles of the Camera

EXPERIMENT B-1. Location and Sizes of Images

A principal function of any camera is the formation of a sharp image by a lens. In Section A you studied the formation of such images. We now wish to learn how to predict where an image will be and how large it will be. These quantities must be known in order actually to design a camera. Thus we need more than the qualitative principles you've learned so far.

In this experiment we will take a more detailed look at lenses and images. You have been given three lenses. Mark them as A, B, and C, using a grease pencil, so that you can identify which lens you are using at a given time.

You should now take out the work sheets at the end of this module. Write answers to questions, and complete the tables on those sheets, as you do the experiment.

Focal Length

Place one of the lenses in a lens holder at the center of the optical bench. Use a distant, well-lighted object (a light bulb across the room will do). Place a screen behind the lens and position the screen to obtain the sharpest possible image of the object. For a very distant object, the rays of light from a given point on the object are all nearly parallel. For this reason the point where the lens axis intercepts the screen, when the image is well-focused on the screen, is the *focal point.* For the distant object you are using, the screen will be very close to the focal point. Measure the distance from the center of the lens to the focal point. This distance is the *focal length.* We will use the symbol f to mean "focal length." Turn the lens around and repeat the measurement.

1. Is there a focal point on the other side of the lens?

2. Measure the focal lengths of each lens on each side of the lens.

3. Are the focal lengths on each side of the lens the same? Record them.

Image and Object Position

You have found that each of the lenses has a focal length. You also know that a lens has two focal points, one on each side of the lens. You shall investigate how the position of an image is related to the position of the object. For reasons which will be apparent later, you will measure image and object distances from the focal points.

4. Place lens A in a lens holder at the center of the optical bench. Record its position and the position of its focal points. With a lighted object on one end of the bench, position the screen until the sharpest image is formed. As indicated in Figure 14, measure the distance from the object to the nearest focal point (call this distance x) and measure the distance from the image (where the screen is located) to the nearest focal point (call this distance x').

   Record these distances and repeat the process for 4 more object positions. Make similar sets of measurements for lenses B and C.

5. Study the data for lens A. How does x' change as x is increased?

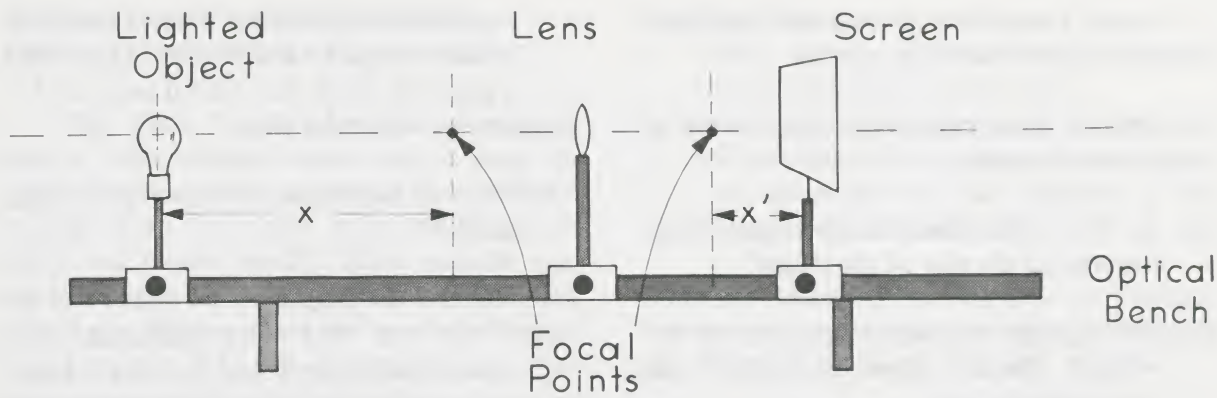


Figure 14.

6. Using a sheet of graph paper, plot a graph of object distance, x, on the horizontal axis and x' on the vertical axis.

   Is the graph a straight line?

7. Very often a curve having this shape represents a reciprocal relationship. By reciprocal relationship, we mean that image distance, x', may be related to object distance, x, through an equation like $x' = (\text{constant}) \times (1/x)$. To test for such a relationship, you would plot, on another sheet of graph paper, a graph of x' on the vertical axis and $1/x$ (divide 1 by each value of x) on the horizontal axis.

   Do these points lie approximately on a straight line?

8. Find the value of the slope (rise divided by run) of the best straight line through these points.

   What are the units for this slope?

9. Repeat steps 7 and 8 for lenses B and C.

10. The value of the slope is related to the value of the focal length for each of the three lenses.

    Try to figure out what that relationship is.

11. Using the symbols x, x', and f, write the relationship you have now found between the image distance and the object distance for a lens. (Recall from algebra the slope-intercept form of the straight line equation: $y = mx + b$. In this case, that becomes: $x' = (\text{slope}) \times (1/x)$.)

Image and Object Size

In this part of the experiment you will find a relationship between the object height and the image height for a camera lens.

12. Place one of the lenses at the center of the optical bench. Position a lighted object at one end of the bench and measure the height of this object.

    What is the object height (symbol H_o)?

13. Move the screen until a sharp image is formed on the screen. Measure the height of this image.

    What is the image height (symbol H_i)?

14. Move the object closer to the lens and position the screen for the sharpest image.

    How has the image height changed?

15. Measure the image heights and object heights for five positions of the object. Also measure the image and object dis-

tances (remember to measure these distances from the focal points).

Record these data in the table found in the work sheets.

16. As the object distance increases, what happens to the size of the image?

17. Plot a graph of image height, H_i, on the vertical axis and object distance, x, on the horizontal axis.

    Is the graph a straight line?

18. As before, the relationship of image height to object distance could be a reciprocal relationship. If so, it would be of the form, $H_i =(\text{constant}) \times (1/x)$. Plot a graph of H_i on the vertical axis and $1/x$ on the horizontal axis.

    What is the value of the slope of this graph?

19. Measure the height of the object and see if you can find some relationship between the slope found in Step 18 and the quantities H_o and f. Try multiplying these numbers, dividing them, etc.

    What do you believe could be a correct equation relating H_i, H_o, f, and x?

Answers to the Items Accompanying the Preceding Goals

1. Form an image of a distant object. Then measure the distance from the image to the lens. That distance is the focal length of the lens.

2. As the object is moved away from the lens, the image moves closer to the focal point (in a direction toward the lens) and the image gets smaller.

3. b. We found a convenient scale to be 5:1. That is, 1 cm on the drawing equals 5 cm in real space. If you use this scale the results are: the image height (1 cm on drawing) is 5 cm, and the distance from the lens to the image (6 cm on drawing) is 30 cm.

4. Image distance = 4 cm; distance from image to lens = 14 cm
   Image height = 2.4 cm

5. a. Closer to the lens.
   b. New image distance = 4 cm

6. a. 80 mm
   b. 8.5 mm
   c. 16.0 mm

RELATIONSHIP BETWEEN IMAGE DISTANCE AND OBJECT DISTANCE

The focal length of a thin converging lens is most readily found by forming an image of a very distant object. Rays of light coming from the same point of a distant object are nearly parallel. Since parallel rays are focused at the focal point, the focal length is then the distance from the lens to the image of the distant object. In Experiment B-1, you found a relationship between the position of the object and the position of the image for a converging lens of a given focal length. If we use f to represent the focal length and x to represent the distance from the object to the focal point, then the image distance, x', can be found from the equation

$$xx' = f^2 \qquad (1)$$

(When an equation is found through experiment, like this, it is called an *empirical equation*.)

RELATIONSHIP BETWEEN IMAGE HEIGHT AND OBJECT DISTANCE

In Experiment B-1, you also found a relationship between the image height and the object height. We can express this relationship in the form

$$H_i/H_o = f/x \qquad (2)$$

where H_i is image height, H_o is object height, f is the lens focal length, and x is the object distance.

LATERAL MAGNIFICATION

This ratio of image height to object height is called *lateral magnification*. Notice that the lateral magnification of a lens depends on the position of the object, as well as on the focal length.

People often use the term "magnify" to mean "make something larger." Lateral magnification, however, may have values less than one. In such cases the image is actually *smaller* than the object.

Question 10.

a. What feature of Equation (1) suggests the reversibility of light rays?

b. What would you observe at the location of an object if you placed another object the same size at the location of the image of the first object?

Example Problem. An object is 18 centimeters from a converging lens of focal length 6 cm. Where is the image located?

Solution. Since we measure object distances from a focal point, the object distance is $x = 18 - 6$, or 12 cm, and $f = 6$ cm. Equation (1) may be solved for x' by dividing both sides by x, so that

$$x' = f^2/x$$

Substituting given values into this equation we have

$$x' = (6 \text{ cm})^2/12 \text{ cm}$$
$$= 36 \text{ cm}^2/12 \text{ cm} = 3 \text{ cm}$$

The image is therefore located 3 cm from the other focal point, or 9 cm from the lens (on the other side of the lens from the object).

Example Problem. What is the lateral magnification in this problem if the object is 1 cm high?

Solution. Given are $x = 12$ centimeters, $f = 6$ cm, and $H_o = 1$ cm. Using Equation (2)

$$H_i/H_o = f/x$$

$$H_i = (f/x)H_o = (6 \text{ cm}/12 \text{ cm}) \times 1 \text{ cm}$$

$$= 0.5 \text{ cm}$$

The image height is ½ that of the object.

Problem 1. Determine the image position for a converging lens of focal length 10 cm when the object is 15 cm from the lens.

Problem 2. What is the lateral magnification in Problem (1)?

Problem 3. An object 10 cm high is 40 cm from a converging lens having a focal length of 20 cm. What are the image position and height?

Problem 4. If an image twice as large as the object is desired, where must the object be placed with respect to a 10 cm focal length converging lens?

IMAGE POSITIONS FOR OBJECTS AT INFINITY

The equations you have found are useful for understanding the camera. For objects which are at great distances compared to the focal length of the lens, the image is formed approximately at the focal point. Actually, the image is larger than a point. What we say is that the plane (like a screen) on which an image is formed, and which intersects the lens axis at the focal point, is called the *focal plane.* You made the observation that such images are formed at the focal plane in Experiment B-1.

A prediction of this behavior also follows from Equation (1). It can be solved for the image position for a very distant object. We have

$$x' = f^2/x$$

When the object is very far away, x is very large compared to f and the ratio of f^2/x approaches zero. But if $x' = 0$, the image is at the focal plane. Fixed focus cameras have a short focal length lens so that, for everything more than a few feet away, x is much greater than f, and objects are imaged at the focal plane, where the film is. In a camera this plane is called the *film plane.* There is never any need to adjust the focus, but close-up shots cannot be taken, and the images obtained are usually rather small.

Question 11. From the equation for lateral magnification, $H_i/H_o = f/x$, you can see that for a fixed object distance, x, the smaller the camera lens focal length, f, the smaller the image on the film.

If this is true, how do you account for the fact that an inexpensive, fixed focal length camera can use large 120 film ($\approx$ 3" X 4") while most variable focus cameras produce images on a smaller, 35 mm film.

VARIABLE FOCUS CAMERAS

A variable focus camera has a lens that can be moved away from or closer to the film plane. When the camera is focused for infinity, the focal plane of the lens is at the film plane. For closer objects, the equation $x' = f^2/x$ predicts that the lens must be moved farther from the film, because the image is farther away from the lens than the focal plane. If the image is to be sharp, it must be focused on the film.

PRINCIPAL RAY DIAGRAMS

As you have learned, the position and size of an image can be found by calculation, using Equations (1) and (2). But there is another procedure which will give the same information. It is called the *method of Principal Ray Diagrams,* or more simply, *ray tracing,* and can be used instead of Equations (1) and (2), or together with those equations. Ray tracing gives a geometric picture of the pattern of light rays, on some convenient scale, as they travel from an object and through a lens to form an image. From Experiments A-1 and A-2, you are already familiar with some of the rules for light ray paths that will allow you to find an image by ray tracing. The method of ray tracing for a converging lens is demonstrated in Figures 15, 16, and 17.

AN EXAMPLE OF RAY TRACING

Using these three rules for light rays, the image of an object can be found by the following procedure: First the lens, along with its axis and focal points, is drawn to some convenient scale. Figure 18 is drawn to a scale where 1 unit on the drawing paper

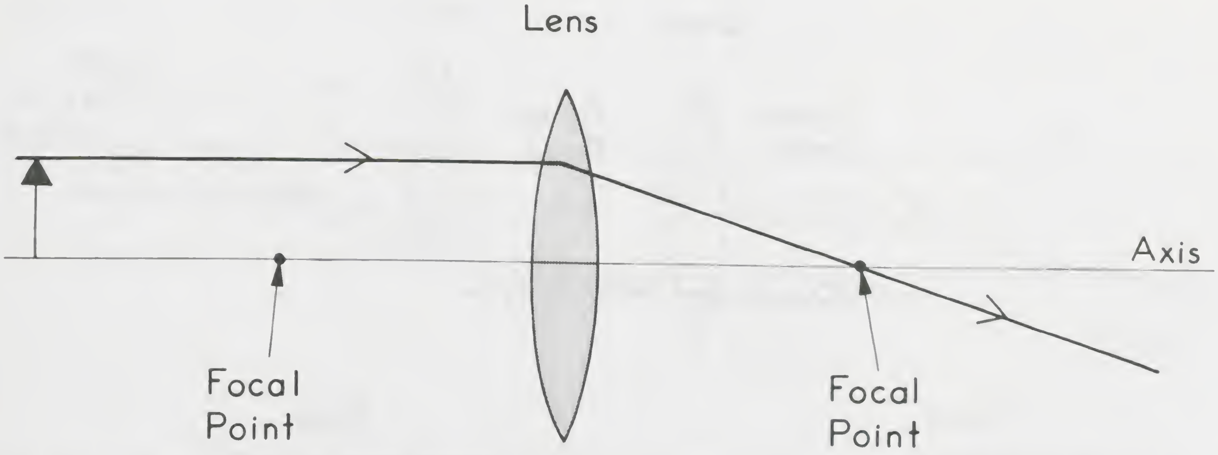


Figure 15. A light ray which approaches a converging lens parallel to the axis, is bent by the lens so that the ray passes through the focal point on the other side of the lens.

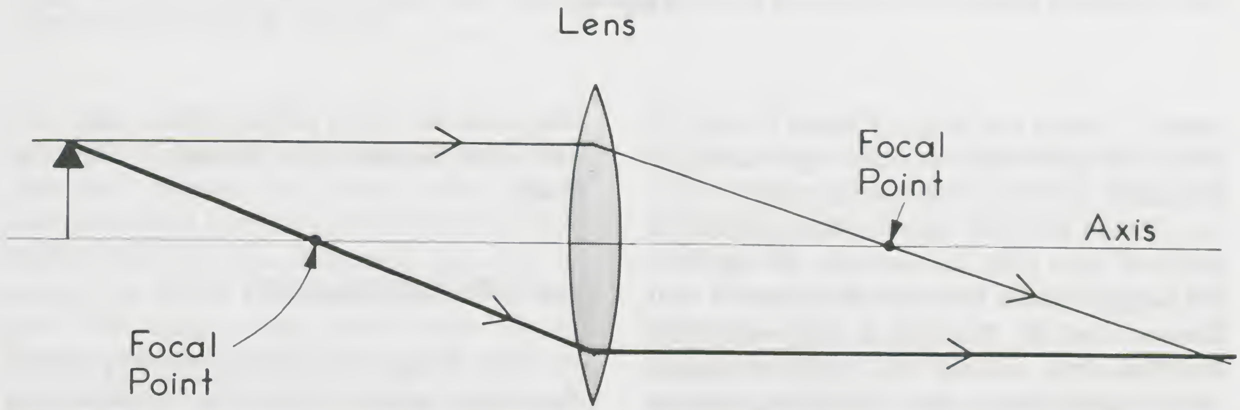


Figure 16. A light ray approaching through the focal point is bent by the lens so that the ray is parallel to the axis on the other side of the lens. (The two rays formed so far would be interchanged if the light paths were reversed.)

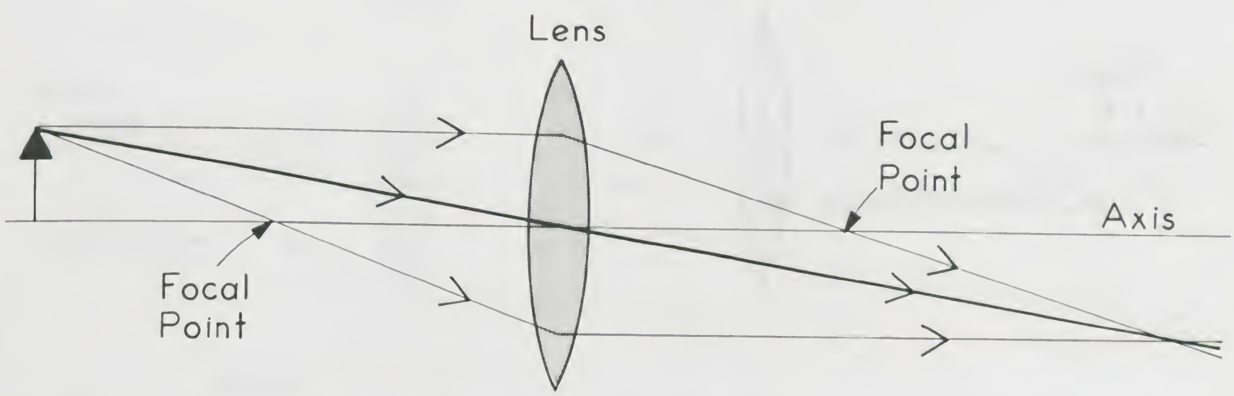


Figure 17. A light ray through the center of the lens comes out undeviated. At the central portion of the lens (and only there) the two faces of the lens are parallel to each other. A ray passing through the center of the lens, therefore, acts just as if it were passing through a flat piece of glass. As you may recall, a light ray through a flat piece of glass is displaced slightly but this displacement for lenses is quite small because the angles of the rays with the axis are very small. For this reason the slight displacement can be neglected.

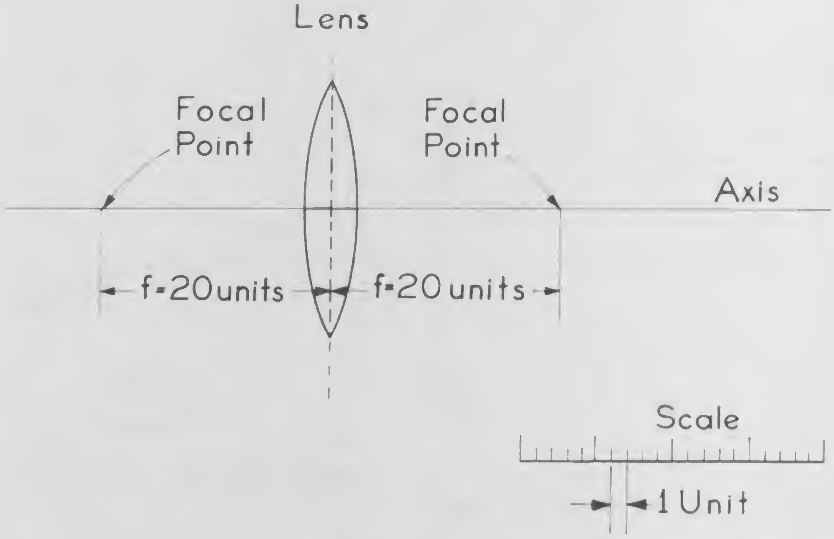


Figure 18.

equals 1 cm in real space. Figures 19 and 20 show the placement of the object and the tracing of the three principal light rays.

Notice the trick we use when one of the principal rays does not actually hit the lens. We simply ignore this fact and pretend that the ray *does* hit the lens in the same plane that the other rays do. This is correct because we are using this ray only to find the position of the image, and we are not claiming that this particular ray is actually there; only rays which hit the lens pass through to form the image.

LOCATING THE IMAGE

The image of the corresponding point on the object appears where the principal rays intersect. Every ray which comes from that

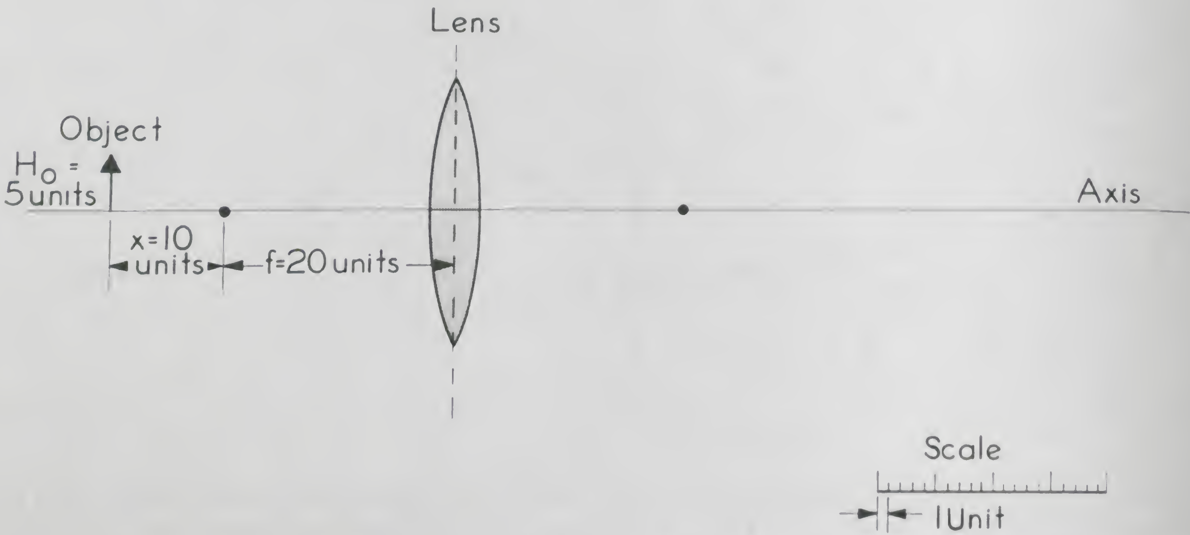


Figure 19. The object distance has been taken at 10 cm, so that x is 10 units. If the height of the object is 5 cm, we construct it 5 units high.

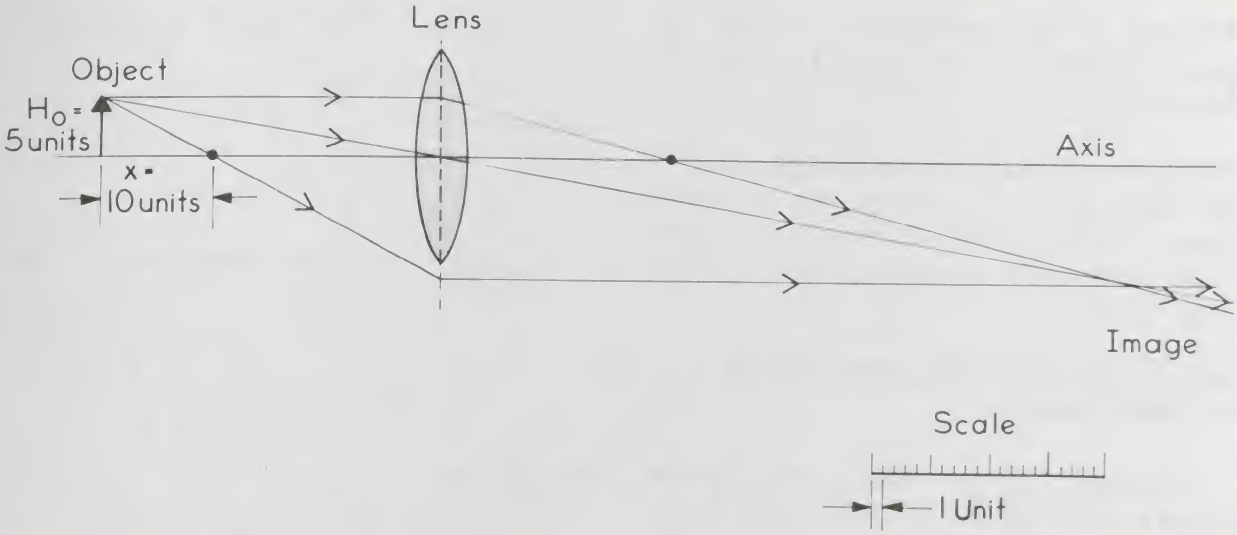


Figure 20. Two (or all three) principal light rays from one point on the object can be traced through the lens, using the rules previously developed.

point on the object and which hits the lens also goes through the image point. But in using principal rays we are using just the rays that are easy to trace. (Actually two rays are enough to locate the image point.) To complete the image, every other point on the object could be treated the same way. However, it is simpler to use the knowledge that, if the object is perpendicular to the axis, so will be the image. Also, an object point on the axis gives an image on the axis. Using this information, the image has been constructed in Figure 21.

From the finished ray trace of Figure 21, the value of x' is 40 units. The value of x' must therefore be 40 cm. The image is inverted, and is 10 units high. Thus, the value of H_i must be 10 cm.

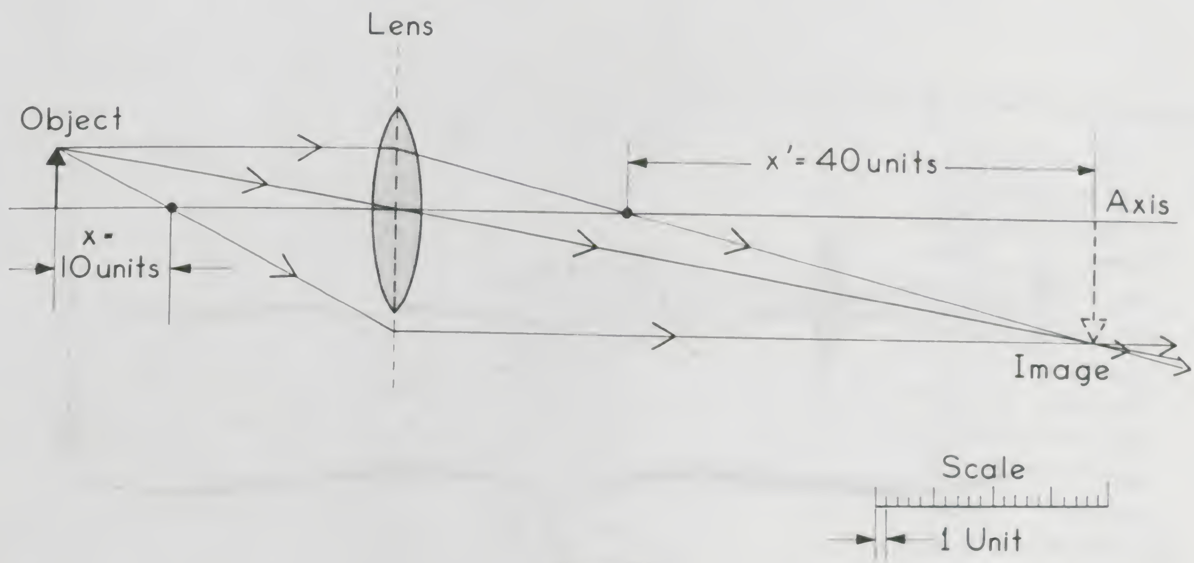


Figure 21.

Problem 5. Use Equation (1) to find the image position for the case illustrated in Figure 21.

Problem 6. By means of a ray diagram, locate the image, and find its height, for an object of height 3 cm, located 10 cm outside of the focal point of a converging lens of focal length 5 cm.

APPLICATION OF LENS PRINCIPLES TO THE CAMERA

Figure 22 shows a side view of a simple camera with various distances and points labeled.

This drawing shows the camera in focus for the closest object for which a clear image can be produced. As the object is moved away from the camera, the lens must be moved closer to the film plane.

Suppose an object is located at a distance, L, from the camera film plane. Then, from Figure 22 the distance, L, is given by

$$x' + 2f + x = L$$

But since x' is always very small compared with x or $2f$, we can neglect this term, so that we have very nearly

$$2f + x \approx L$$

(The symbol $\approx$ means "approximately equal to.")

Solving for x

$$x \approx L - 2f$$

Let us calculate the image distance x'. We have

$$xx' = f^2$$

Substituting in for x

$$(L - 2f)x' \approx f^2$$

Solving for x'

$$x' \approx f^2/(L - 2f)$$

For many uses of the camera, f is much less than L, so that we can write this equation as

$$x' \approx f^2/L$$

For a camera having a 50 mm focal length lens, we can calculate values of x' for several distances, L. Table I shows those image distances, as well as distances from the lens to the film plane $(x' + f)$ for various object positions.

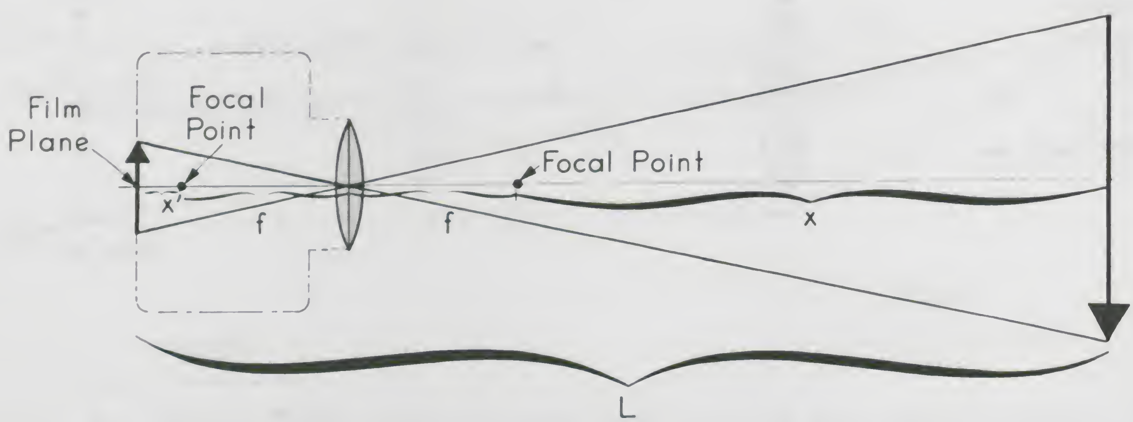


Figure 22.

FOCUSING A CAMERA

From Table I, you can conclude several things about a camera which has a 50 mm focal length lens. For an object which is 100 feet or more away from the camera, the distance from the lens to the camera is, within less than a tenth of a millimeter, just the focal length itself, 50 mm. You can conclude, therefore, that for objects at large distances, the distance from film plane to lens is the focal length, f, of the camera lens. Also, this is the closest distance from the film plane for the lens.

You can also see from Table I that, when the object is moved *toward* the camera, the lens must be moved *away* from the film plane. For a 50 mm camera, the lens must be 57 mm away from the film plane for an object 1.5 feet from the film plane to be in focus. From this fact you can conclude that the amount of lens *travel* required in a 50 mm focal length camera is 7.0 mm, if the camera is to focus on objects as close as 1.5 feet.

The lens *travel* is just the difference of the image distances for closest and farthest object positions. For the farthest object position, the image distance is zero. Therefore, the travel is the same as the image distance for the closest object position.

Example Problem. A camera with a 100 mm focal length lens is to be designed to focus on objects from 2.5 feet to infinity. How far must the lens move as the focus is adjusted from infinity to 2.5 feet? (i.e., what is the lens travel?)

Solution. We are given that $L = 2.5$ feet ≈ 76 cm and that $f = 100$ mm $= 10$ cm. Calculating x', we have

$$x' \approx \frac{f^2}{L - 2f}$$

$$\approx \frac{100\ \text{cm}^2}{76\ \text{cm} - 20\ \text{cm}}$$

$$\approx 1.79\ \text{cm}$$

The lens must have a travel of 17.9 mm.

Table I.

Image distance (x')	Distance from lens to film plane $x' + f$	Distance, L, from object to film plane
7.0 mm	57.0 mm	1.50 ft (45.7 cm)
4.9 mm	54.9 mm	2.00 ft (61.0 cm)
1.8 mm	51.8 mm	5.00 ft (152 cm)
0.8 mm	50.8 mm	10.00 ft (305 cm)
0.6 mm	50.6 mm	15.00 ft (457 cm)
0.3 mm	50.3 mm	25.00 ft (762 cm)
0.08 mm	50.08 mm	100.00 ft (3048 cm)
0.008 mm	50.008 mm	1000.00 ft (30,480 cm)
0.0	50 mm exactly	∞

Problem 7. Calculate the amount of lens travel required for a camera having a 30 mm focal length lens. The lens should focus on an object as close as 3 feet (3 ft ≈ 91 cm). What width should the camera case be?

Problem 8. A small "fixed focus" camera has a lens with a focal length of 40 mm. If objects are acceptably focused for image positions which are within 1.0 mm of the film plane, what is the closest distance for which this camera can take clear pictures?

IMAGE SIZE IN A CAMERA

What are the differences between one camera and another in terms of image size? You have learned that image size is given by

$$H_i = H_o f/x$$

or, in terms of L,

$$H_i \approx H_o f/(L - 2f)$$

Let us look again at a camera which has a 50 mm focal length lens and which has a closest in-focus distance of 1.5 feet (45.7 cm). If this camera uses 35 mm film, let us determine the largest object which can be placed at 1.5 feet and have its image fill a frame. A frame of 35 mm film has an exposure surface with dimensions of about 24 mm wide and 36 mm long. The rest of the film width is used for the film borders and sprocket holes. The maximum image height would be the width of the exposure surface, about 24 mm; therefore

$$2.4 \text{ cm} \approx H_o(5.0 \text{ cm})/(45.7 \text{ cm} - 10 \text{ cm})$$

or

$$H_o \approx [(2.4 \text{ cm})(35.7 \text{ cm})]/5.0 \text{ cm} = 17.1 \text{ cm}$$

(This is about 6¾ inches.)

Similarly, the object could have a maximum width of about 25.7 cm (about 10.8 inches).

Problem 9. What is the height of the image on 35 mm film of a man who is 5'11" tall (180 cm) and is standing 25 feet (762 cm) from the film plane of a camera with a lens having a focal length of 50 mm?

SUMMARY OF SECTION B

The following statements summarize the concepts, definitions, and principles you have learned in this part of the module. Some of these statements are *empirical* equations.

The distance from the focal point of a converging lens to an object located on the same side of the lens is called the *object distance.* Object distance is represented by the symbol x.

The distance from an image produced by a converging lens to the focal point on the same side of the lens is called the *image distance.* Image distance is represented by the symbol x'.

The relationship of image distance to object distance for a lens of focal length, f, is given by the equation

$$xx' = f^2$$

The *lateral magnification* of a converging lens is defined as the ratio H_i/H_o, where H_i is the height of the image and H_o is the height of the object. Values of lateral magnification may be less than, equal to, or greater than one; thus an image may be smaller than the object, the same size as the object, or larger than the object.

The relationship of lateral magnification, H_i/H_o, to object distance for a lens of focal length, f, is given by

$$H_i/H_o = f/x$$

The position and height of an image produced by a converging lens can be found by *the method of Principal Ray Diagrams.* This method consists of the following steps:

1. Draw a vertical line at the position of the lens, a lens axis, and focal points located

at distances which are scaled conveniently.

2. Draw an object with its base on the axis and its height reduced by the scaling factor selected in Step 1. Place the object at an object distance which is scaled by the same factor.

3. Construct a line from the top of the object parallel to the axis to a point on the vertical line representing the lens. From this point, a line should be constructed to pass through the focal point on the other side of the lens from the object.

4. Construct a line from the top of the object through the focal point on that side of the lens to a point on the vertical line representing the lens. From this point, construct a line parallel to the lens axis.

5. Construct a straight line from the top of the object through the point of intersection of the vertical line and the lens axis.

6. The three principal rays you have drawn should intersect at one point. This point is the image point corresponding to the top of the object. Draw in the rest of the image.

7. Measure the scaled image height and scaled image distance and use the scale factor to find the actual image height and actual image distance.

The amount by which a camera lens of focal length f must move away from the film plane of a camera, as the camera focus is adjusted from a distant object to an object at the closest position, L, is given approximately by the equation

$$\text{Lens travel} \approx (f^2)/(L - 2f)$$

The height of an image on the film of a camera having a focal length, f, for an object of height H_0 located at a distance, L, from the film plane of the camera is given approximately by the equation

$$\text{Height of image} \approx (H_0 f)/(L - 2f)$$

GOALS FOR SECTION C

The following goals state what you should be able to do after you have completed this section of the module. The example which follows each goal is a test item which fits the goal. When you can correctly respond to any item like the one given, you will know that you have met that goal. Answers appear immediately following these goals.

1. *Goal:* Know how to derive lens equations.

   Item: Referring to the principal ray diagram shown below, identify pairs of similar triangles which would be used to prove each of the following equations:

   a. $H_i/H_o = f/x$
   b. $H_i/H_o = x'/f$
   c. $H_i/H_o = (x' + f)/(x + f)$

   (Designate each triangle by using the symbol Δ in front of three letters which are at vertices of the triangle, as in ΔPCF_1.)

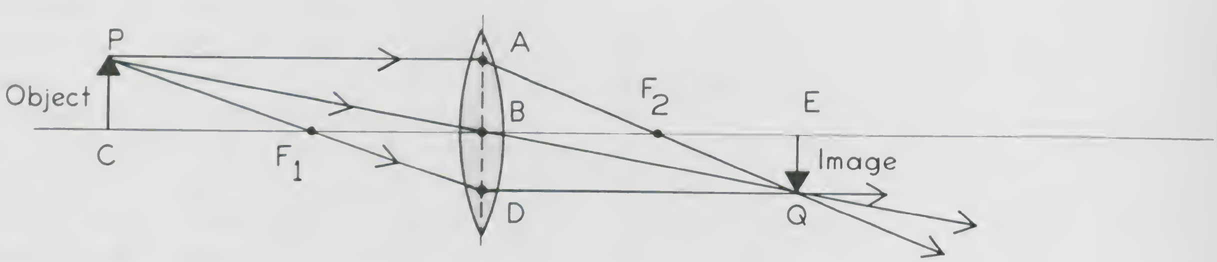
2. *Goal:* Be able to apply the method of principal ray diagrams to a lens used as a magnifying glass.

   Item: A thin converging lens of focal length 15 cm has an object of height 4 cm placed on the principal axis 10 cm from the lens.

   a. Construct a principal ray diagram.
   b. *From your diagram,* determine the distance from the image to the lens.
   c. From your diagram, determine the height of the image.
   d. What is the name we give to this kind of an image?

3. *Goal:* Know the relationship of image height for a given distant object to focal length for a converging lens.

   Item: The disc of the moon subtends an angle of 1/60 radian, as observed at the location of a certain lens. If the image of the moon formed by this lens has a diameter of 5 mm (0.5 cm), what is the focal length of the lens?



4. *Goal:* Know the definition of f number, and understand the relationship of image brightness to f number.

   Item: Some typical f numbers on a camera lens are 1.4; 2; 2.8; 4; 5.6; 8; 16. If the lens has a focal length of 70 mm,

   a. What is the diameter of the lens aperture for an f number of 1.4?
   b. How much brighter is the image for an f number of 4 than an f number of 16?

5. *Goal:* Understand the relationship of film speed to f number and exposure time for a camera.

   Item: Suppose that, to get a correct exposure using ASA 25 film, you have to set your camera at speed f/4 and 1/60 second. If you have another camera along, which is loaded with ASA 160 film, and which is set at f/5.6, what shutter speed is needed for a correct exposure?

Answers to the Items Accompanying the Preceding Goals

1. a. $\Delta F_1 BD$ is similar to $\Delta F_1 CP$

   b. ΔABF_2 is similar to ΔQEF_2

   c. ΔPCB is similar to ΔQEB

2. Scale: 1 cm on graph = 10 cm actual. H_i = 1.2 cm on graph = 12 cm actual. Distance from image to lens = $f + x'$ = 3.0 cm on graph = 30 cm actual.

   b. 30 cm

   c. 12 cm

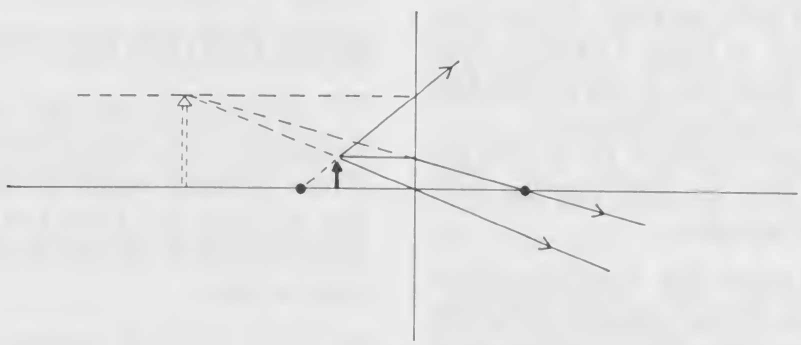
   d. Virtual image

3. f = 30 cm

4. a. D = 50 mm

   b. 16 times brighter

5. t = 1/196 second



Problem 2a.

SECTION C

Derivations of Lens Equations, The Simple Magnifier and f Numbers for Cameras

LATERAL MAGNIFICATION

The ray tracing procedure introduced in the last section is a powerful tool for the further investigations of lenses. For example, the equations $xx' = f^2$ and $H_i/H_o = f/x$ can be derived from the ray tracing rules and geometry. To show that these equations follow from a ray diagram, look at Figure 23,which shows the object and image for a converging lens with the three principal rays drawn in.

The two shaded triangles on the left are similar because they are right triangles with equal corresponding angles.

Problem 10. Identify the "corresponding" angles for the two shaded triangles on the left in Figure 23. Then prove that the angles are equal.

The ratios of corresponding sides of similar triangles are the same, so that

$$H_i/f = H_o/x$$

or, rearranging

$$H_i/H_o = f/x \qquad (2)$$

H_i and H_o are what appear as the shorter legs of the similar right triangles, and are one set of corresponding sides. The legs x and f appear as the longer legs and are another set of corresponding sides. We see that this is just Equation (2) for lateral magnification.

IMAGE POSITION EQUATION

A few more steps are required to derive Equation (1). We seiect the two other shaded similar triangles, which are on the right of the lens in Figure 23. These two triangles are also similar and again H_o and H_i are corresponding sides, so that

$$H_i/H_o = x'/f \qquad (3)$$

We can now set H_i/H_o of Equation (2) equal to H_i/H_o of Equation (3), so that

$$x'/f = f/x$$

Multiplying both sides of this equation by fx, we have

$$xx' = f^2 \qquad (1)$$

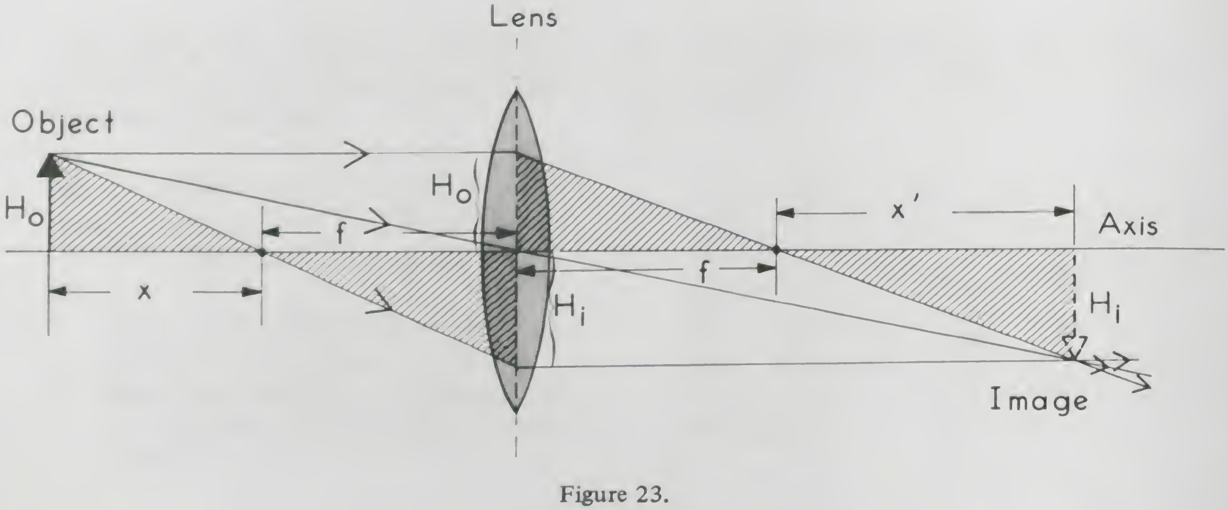


Figure 23.

Problem 11. We can derive another relationship between lateral magnification and other quantities.

$$H_i/H_o = (x' + f)/(x + f) \qquad (4)$$

Construct a diagram like that in Figure 23, label the triangles which you have taken to be similar, and prove that this relationship is correct.

OBJECT INSIDE THE FOCAL POINT

Almost everyone at one time or another has used a simple *magnifying glass.* A magnifying glass is a converging lens. While using a magnifying glass, or while doing experiments with converging lenses in this module, you have probably observed how images change as you move a converging lens away from objects.

Try the following steps to see again how it goes:

1. When the object is close, you see through the lens an upright image which is larger than the object.

2. As you move the lens away from the object, the image becomes larger, until it blurs out.

3. As you continue to move the lens away you see an inverted image. The change from upright to inverted image occurs as the object passes through the focal point.

Let us now determine the location and height of an image for an object which is located *inside* the focal point of a lens. We can draw the principal rays in this case as shown in Figure 24.

Two of the rays are drawn in exactly the same manner as before: one ray is constructed parallel to the axis, and another ray is constructed through the lens center. The first of these passes through the focal point on the right and the second continues straight through. The third ray does not go through the focal point on the left, but rather it is drawn so that it strikes the lens at the same angle and position as a ray coming from that focal point *would* have done. Since the bending action of the lens depends only on this angle and position, the ray comes out parallel to the axis.

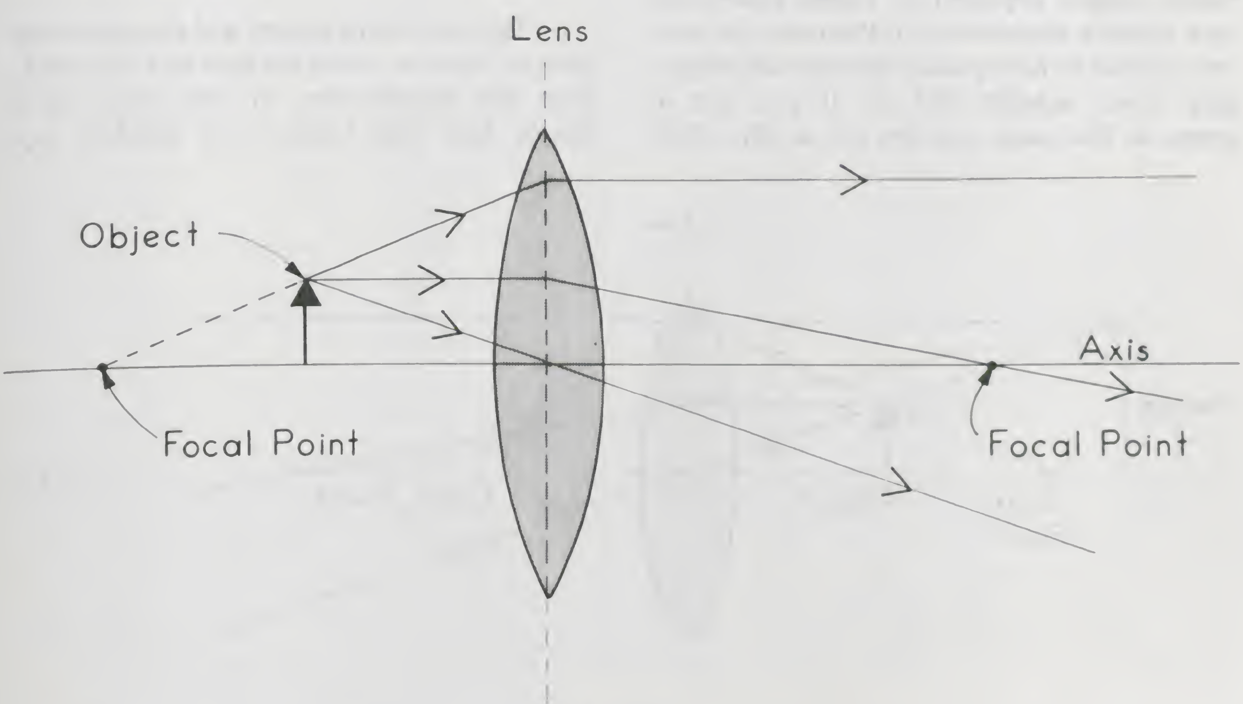


Figure 24.

bending action of the lens depends only on this angle and position, the ray comes out parallel to the axis.

Notice that these three rays coming from the top of the object do not intersect anywhere after they pass through the lens. They are moving away from each other and are therefore said to be *diverging.*

Where is the image? Or is there one? We can get some hint about the image by examining our earlier ray diagrams more closely. In Figure 23 the rays diverge *after* they have formed an image. But you can see that image by looking toward the lens from the right. You see the object as if it is actually at the image position. What happens is that the lens of the eye converges those diverging rays, so that they are focused on the retina.

In Figure 24, the rays are already *diverging* when they leave the lens. If you look through the lens from the right, your eye follows the ray backward in straight lines, and the image *appears* to be at the point where the rays would intersect if they were extended backward. As shown in Figure 25, this image is on the same side of the lens as the object, but farther from the lens.

The image in Figure 25 is different from the images we have studied so far. All the earlier images appeared at places where the rays actually intersected. In this case, the rays only *appear* to have passed through the image; they never actually did so. If you put a screen at the image position (or at any other position), an image would not be focused on the screen. This kind of image is called a *virtual image;* the ones we saw earlier are known as *real images.*

We have used a principal ray diagram to predict that, when the object is inside the focal point, there will be a virtual image which is erect (right side up) with respect to the object. For simple lenses, real images are inverted (upside down).

Question 12. Can the virtual image produced by a converging lens be smaller than the object?

THE MAGNIFYING GLASS

Although the camera does not make use of a virtual image, there are other optical instruments which do. The most basic is the simple magnifier or magnifying glass. You have seen from Figure 25 that the virtual image is larger than the object. When you use a magnifying glass, as shown in Figure 26, you are placing an object inside the focal point and looking through the lens at the enlarged virtual image.

COMPOUND LENSES

The ray tracing theory and the equations derived from it, which we have just discussed, treat the imaging lens of the camera as a simple lens that bends every incident ray

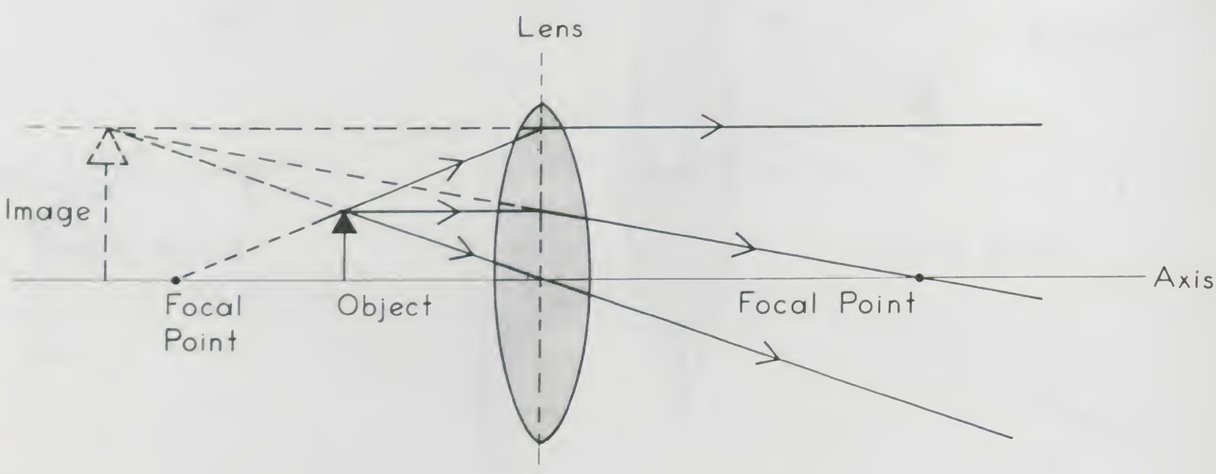


Figure 25.

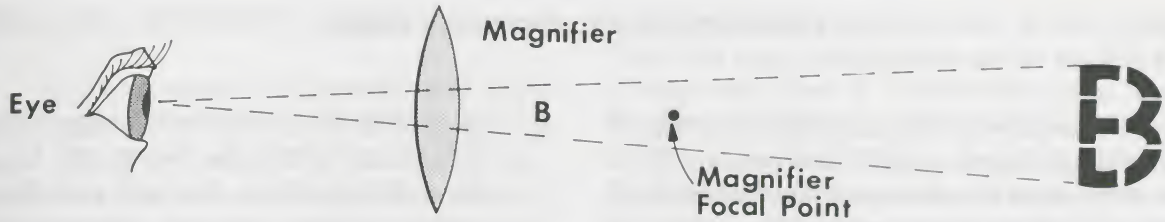


Figure 26.

which is parallel to the axis so that the ray passes through the focal point on the other side of the lens. But, as you have already discovered in Experiment A-2, actual simple lenses do not do this perfectly. A camera with a "good" lens may provide considerably improved focusing. However, such lenses are complex combinations of simpler lenses, although they are often within a single housing.

The correction of chromatic aberration requires the combination of simpler lenses of different glass cemented together to form what is called an *achromat.* What we have done so far in this module is to create an idealized picture (or "model") of lenses. Real lenses give the results predicted by the model only insofar as they fit the model. If we wish a truer picture, we must change the model to correspond more closely with real lenses. You can try the predictions of our simple model for a more complex lens and also gain some insight into the modifications needed to improve the model by doing the following experiment.

EXPERIMENT C-1. Compound Lenses

A *compound lens* consists of two or more simple lenses combined into one device. In some cases the compound lens consists of two or more lenses which are made of different materials and which are cemented together. In other cases the compound lens is made of two or more lenses placed within the same housing, but at some distance from each other.

You should now take out the work sheets at the end of this experiment. Write answers to questions, and complete these sheets as you do the experiment.

1. By the methods which you have learned earlier, locate the focal point on one side of the lens. Since the compound lens is quite thick, measure distances from the center of the compound lens.

2. Locate the focal point on the other side of the lens system. As you can see, the two distances are quite different. This means you cannot use the distance from the focal point to the lens (or to the center of the lens) as the focal length. You must use some other method to calculate the focal length for this thick lens.

3. Place an object (a lighted bulb) outside the focal point on one side of the lens. Measure the object distance (distance from focal point to object). Also measure the object height.

4. Using a screen, locate the real image on the other side of the lens. Measure the image distance (distance from focal point to image). Also measure the image height.

5. For a thin lens you found that $xx' = f^2$, where f was the distance from a focal point to the lens. However, the method of finding the focal length by measuring the distance from the lens to the image for a distant object does not work for a compound lens. As you observed, the compound lens has focal points located at *different* distances on each side from the center of the lens system.

   Suppose we *assume* that the relationship $xx' = f^2$ is valid for this compound lens. Use the image and object distance measurements of Steps 3 and 4 to determine the focal length (since $xx' = f^2$, $f = \sqrt{xx'}$).

6. Let us now check this value of f to see if it is consistent with other quantities. Let us look at the lateral magnification. Using the image and object heights, measured in Steps 3 and 4, what is the value of the ratio H_i/H_o? How does this value compare with the ratio, f/x?

7. Another ("operational") way to find the value of the focal length for a compound lens is as follows:

   a. Form an image of a distant object with the compound lens.
   b. Form an image of the same distant object with a thin lens. Compare the image height for the thin lens with the image height for the compound lens. Use a selection of lenses which permits you to vary the image height (lenses of different focal lengths). When you finally find a thin lens which produces an image of the *same* height as that produced by the compound lens, measure the focal length of the thin lens as the image to lens distance. This focal length is then the same as that of the compound lens.

Use this procedure to find the focal length of the compound lens.

THIN AND COMPOUND LENSES

As you observed in Experiment C-1, the focal length of a compound lens cannot be found simply by measuring the distance between the lens and an image formed by a distant object. Instead a compound lens can be compared with an equivalent simple lens which gives the same image height. The focal length of the compound or thick lens is taken to be the same as that of the simple or thin lens. If you have already located the focal points, this procedure will allow you to use Equation (1) to calculate the image position and Equation (2) to calculate image height on the film. These relationships are important in photography because they provide that any two quite different lenses with the same focal length will produce the same size image of the same object. No matter how complex the lens or lens system, those with longer focal lengths produce larger images.

AN OPERATIONAL DEFINITION OF FOCAL LENGTH

It is inconvenient to search every time for a thin lens with the same focal length as the compound lens you wish to know about. Actually, you don't really need to do so. There is a mathematical procedure which can be used to give the focal length. This makes use of measurements on the thick lens image.

We shall illustrate this procedure by showing how to calculate the focal length of a thin lens using measurements of the image. Then the same calculations can be applied for a thick lens, since it will have the same focal length as the thin lens if it produces an image of the same size. This is doing exactly the same thing mathematically as you did by substituting thin lenses. Figure 27 shows the real image of a distant object, formed by a thin lens.

The rays shown coming from the top and bottom of the object go through the center of the lens to the corresponding points on the image. Because the object is very distant, the image is located in the *focal plane.* (A plane passing through the focal point and perpendicular to the lens axis.) These two rays define the angle subtended by both the object and the image. It has been labeled α. If α is in radians, then, approximately

$$\alpha \approx H_i/f$$

This approximation is good when the angle is small. As shown in Figure 28, the image height is not much different from the length of the arc drawn, using the point O as a center.

For small angles, H_i and the arc length are very nearly the same. For example, when α is 4°, the difference in lengths is less than 0.08%. Since the agreement is so good, we'll write the approximation as an equality.

$$\alpha = H_i/f$$

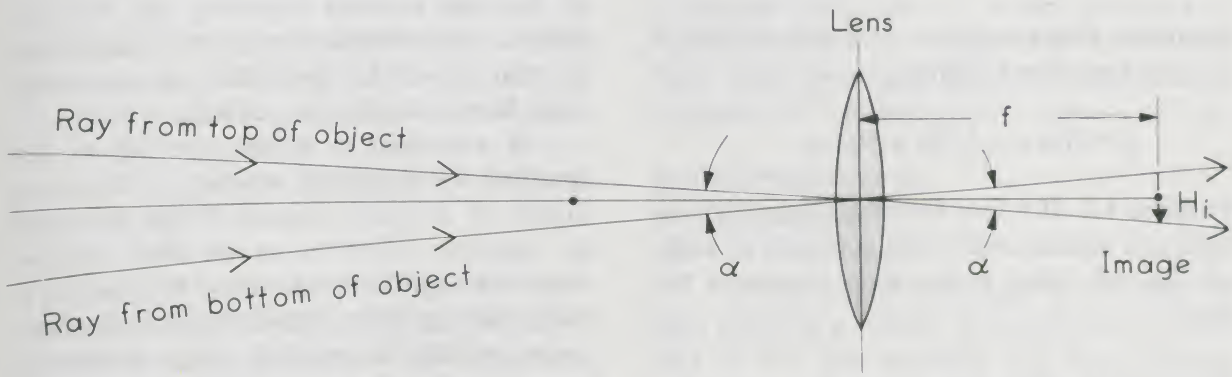


Figure 27.

Figure 28.

Multiplying both sides of this equation by f, we have

$$H_i = \alpha f \tag{5}$$

Dividing both sides of the equation by α, we have

$$f = H_i/\alpha \tag{6}$$

By observing a distant object through a lens, then measuring the image height and the angle subtended by the distant object, you can use Equation (6) to calculate the focal length. (You will probably want to measure the angle in degrees, then convert it to radians. To make the conversion to radians, use the formula: radians = (3.14 X degrees)/180.)

The same measurements and calculation can be done for the focal length of a thick lens.

Example Problem. A distant tree subtends an angle of .05 radian (about 3°) from a certain lens. The lens produces an image 2.5 cm high. What is the focal length of the lens?

Solution. Given are α = .05 rad and H_i = 2.5 cm. Equation (6) gives

$$f = H_i/\alpha = 2.5/.05 = 50 \text{ cm}$$

Problem 12. If a lens forms an image 1.7 cm high of a distant object that subtends an angle of .04 rad, what is the focal length of the lens?

Problem 13. What size image is formed of a person who is 2 m tall and far enough away to subtend an angle of .08 rad, with a lens of 20 cm focal length?

Note that Equation (5) indicates that the image height is proportional to the focal length of the lens, if the object subtends a small enough angle. Actually this result is true regardless of the angular size of the object, as could be shown by a more advanced analysis. The height of the real image of an object of a given angular size is always directly proportional to the focal length of the lens.

Problem 14. A photographer notes that a distant water tower fills about ¼ of his viewing field when he uses a 50 mm focal length lens. What focal length lens should he use to get the image of the tower to fill the whole field?

AMOUNT OF LIGHT ENTERING A LENS

Some cameras have what are called *f stops* or *f numbers,* which can be adjusted. If you open the back of such a camera, set the shutter so that it can be held open, and look through the lens, you will see a *diaphragm* behind the lens. The diaphragm is an arrangement which allows the photographer to change the size of the hole through which the light passes as it goes into the camera. As the f number is decreased, this opening increases in size. As the f number is increased, the opening gets smaller. Through this adjustment, the size of the lens aperture (opening) can be controlled. To understand why the camera lens aperture *should* be controlled, we must learn some facts and principles of light.

If you have a square opening as the aperture for a *camera obscura,* as shown in Figure 29, a certain amount of light can enter the aperture. Now let us see what happens when the length of each side of the opening is made twice as large. Figure 30 shows the light cones entering an aperture which is twice as long on each side as the one shown in Figure 29.

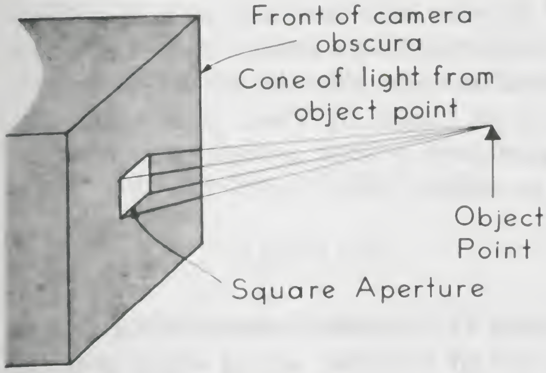


Figure 29.

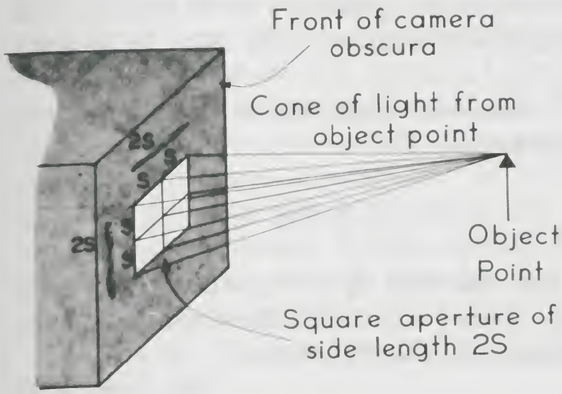


Figure 30.

As you can see, this larger aperture has four light cones, each of which is the same size as the single cone for the smaller aperture. Thus, under the same conditions, four times as much light can enter this larger aperture.

This example illustrates the fact that the amount of light which can enter an aperture is proportional to the area of the aperture.

Question 13. Suppose a *camera obscura* has a square aperture having a side length of s. If the aperture admits a certain amount of light, how much more light is admitted if the aperture side length is increased by a factor of three?

As you know, cameras do not have square apertures; they have circular apertures. Since the amount of light entering an aperture depends upon the *area* of the aperture, we need to examine how the area of a circle changes as the diameter is increased.

The formula for the area of a circle is

$$A = \pi(D^2/4)$$

where D is the diameter of the circle and A is the area of the circle.

Now suppose a circular aperture of a diameter D_1 admits a certain amount of light E_1. How much light would be admitted if the diameter of the aperture were doubled? We know that the amount of light is proportional to the area; therefore,

$$(E_2/E_1) = (A_2/A_1)$$

Then, using the formula for the area of a circle, we have

$$\frac{E_2}{E_1} = \frac{\pi D_2^2/4}{\pi D_1^2/4} = \frac{D_2^2}{D_1^2} \tag{7}$$

Now, since $D_2 = 2D_1$, we can replace D_2 in Equation (7) by $2D_1$. Doing this, we get

$$\frac{E_2}{E_1} = \frac{(2D_1)^2}{D_1^2} = \frac{4D_1^2}{D_1^2} = 4$$

Thus $E_2 = 4E_1$, and the amount of light is four times greater.

Problem 15. When the f number on a camera is changed from 5.6 to 1.4, the diameter of the lens aperture increases by a factor of 4. How much more light enters the camera at an f number of 1.4 than at an f number of 5.6?

BRIGHTNESS OF A CAMERA IMAGE

You have just seen that the amount of light entering a camera is proportional to the area of the lens aperture. The lens aperture size can be changed in many cameras through adjustments of f numbers. The brightness of

the image produced is directly proportional to the amount of light entering the camera. Thus, we can conclude that the brightness, B, of an image is proportional to the area of the lens aperture, or to the square of the diameter of the aperture. In symbols, we could write these properties as,

$$B \propto A$$

$$B \propto D^2$$

But what else does the brightness of an image depend upon? Consider an image produced by a camera lens having a focal length of 50 mm. You have already learned that if we double this focal length, and use a 100 mm lens, the image height is doubled. But, if the diameter of the aperture is the same in both cases, the amount of light entering the camera is the same. What if the image is that of a square object? For the 50 mm lens, suppose the image is 10 mm high. Then with the 100 mm lens, the image will be 20 mm high. The same amount of light has to be spread out on the film to cover a square which is twice as wide and twice as high. The same amount of light must cover an area *four* times greater. You can see that the brightness of the image must be *reduced* for the 100 mm lens by a factor of 4.

This result is generally true. The brightness of an image is *inversely* proportional to the image area. Since the image area is proportional to the square of the height of the image (even for images which are not square) we can write the relationship of image brightness to image height as

$$B \propto 1/H_i^2$$

Problem 16. A camera has a 50 mm lens and produces an image with a certain brightness. When the camera lens is changed to a 150 mm telephoto lens, the image height increases by a factor of three. Assuming that the aperture size remaines the same, how much does the brightness of the image change?

We now have two relationships involving the brightness of an image. One relationship involves the lens aperture, D, and the other, the image height, H_i. These relationships can be combined to form a single proportion. It can be written,

$$B \propto D^2/H_i^2$$

Problem 17. Suppose a camera with a 40 mm lens has an f number setting which gives an aperture having a diameter of 5 mm. How much does the image brightness change if the 40 mm lens is replaced by an 80 mm lens and the aperture diameter is increased to 20 mm?

You will recall the relationship for a distant object

$$H_i = \alpha f$$

In this equation, H_i is proportional to f for a given distant object at a fixed position. Thus, we can write the proportion

$$B \propto D^2/H_i^2$$

as

$$B \propto D^2/f^2$$

or

$$B \propto (D/f)^2$$

We have found that the brightness of a camera image is proportional to the square of the lens aperture and inversely proportional to the square of the lens focal length.

CAMERA EXPOSURE TIMES

Many cameras have an adjustment for the length of time during which the shutter is open. During this time, the lens aperture is uncovered so that light can enter the camera. The total amount of light entering the camera

is directly proportional to this time t. The total amount of light is also proportional to the image brightness. We can write this proportion as,

$$\text{(total amount of light)} \propto Bt$$

or

$$\text{(total amount of light)} \propto (D/f)^2 t \qquad (8)$$

Camera film exposure is determined by the total amount of light entering a camera. For a given type of film, there is some amount of light which will expose the film correctly. We shall call this optimum (correct) amount of light *exposure.* If we change the lens aperture, lens focal length, or exposure time, we still want the exposure to be the *same* for the same film. This means that we want the total amount of light entering the camera to be the same so that the film is exposed the same amount.

What we must have for such a constant exposure is that

$$(D/f)^2 t = \text{constant} \qquad (9)$$

CAMERA f NUMBERS

The ratio D/f has occurred in several relationships you have examined so far. The reciprocal of this ratio, f/D, is the *f number.* We symbolize f number by $f\#$, and in symbols define $f\#$ by

$$f\# = f/D \qquad (10)$$

Using f number, we can write the condition for correct exposure of camera film as

$$(1/f\#)^2 t = \text{constant}$$

or

$$t/(f\#)^2 = \text{constant}$$

This means for two different exposure times

$$\frac{t_2}{t_1} = \left(\frac{f\#_1}{f\#_2}\right)^2 \qquad (11)$$

Example Problem. What is the f number of a 50 mm diameter lens with a focal length of 20 cm?

Solution. Given are D = 50 mm and f = 20 cm. Equation (10) can be used directly $f\# = f/D$ = 20 cm/5 cm = 4. This would be an f/4 lens.

Problem 18. What is the f number of a 10 mm diameter lens with a focal length of 3 cm?

Problem 19. What is the focal length of an f/16 lens having a diameter of 75 millimeters?

Question 14. To double the brightness of a camera image, what adjustment should be made to the f number?

Question 15. Some typical f stops or f numbers on a good camera lens are 1.4, 2, 2.8, 4, 5.6, 8. These are the f numbers for the various aperture openings that can be clicked in by turning the barrel of the lens. What property of the lens is being changed by these adjustments? What are the squares of these numbers (to the nearest integer)? What do these numbers imply about the areas of the successive apertures? What do they imply about the brightness of the images?

In using a camera we usually want the smallest f number possible (widest opening) because this setting allows the shortest exposure time. However, as you discovered in the first experiment, a larger aperture also gives less depth of field. So there is a trade-off to be made in any photograph between exposure time and depth of field, depending on the subject of the picture. If the subject is moving rapidly, a short exposure time is needed to stop the blurring, and therefore a low f

number is required which also implies little depth of field. If the subject is still, the camera can be "stopped down" to a high f number in order to give a greater depth of field; then a longer exposure time can be used.

Problem 20. For a given type of film in a camera you get a correct exposure of a still subject using a 50 mm lens set at 1/30 second exposure time and f/8. You then decide to get a close up picture of a distant, moving object. You set the time at 1/120 second and replace the 50 mm lens with a 100 mm telephoto lens. What f number should you use?

FILM SPEED

You have learned that camera film exposure, for a given type of film, is determined by the total amount of light entering the camera. We had the proportion,

$$\text{(total amount of light)} \propto (D/f)^2\, t$$

or

$$\text{(total amount of light)} \propto t/(f\#)^2$$

Some film needs very little light for a correct exposure, and such film is said to be *fast.* Other film needs more light, and is said to be *slow.* Fast film has the disadvantage that the pictures are more grainy and have less detail that can be seen than slow film. Film speeds are often expressed in numbers like ASA. (These numbers are standards set by the American Standards Association and widely used by film manufacturers.) The faster the film the higher the number. Since high speed film requires small amounts of light, film speed numbers are inversely proportional to the total amount of light entering the camera.

If we let Z stand for film speed, then we can write the proportion

$$Z \propto (f\#)^2/t \tag{12}$$

Example Problem. High speed Ektachrome color film has a speed of ASA 160. Kodachrome II film has a speed of ASA 25. Suppose that you take a correct exposure of a fixed scene using ASA 25 film at f/5.6 and at an exposure time of 1/30 second. For an exposure time of 1/60 second, what f number must you use for a film speed of ASA 160?

Solution. From Equation (12), we have

$$\frac{Z_2}{Z_1} = \left(\frac{\text{f}\#_2}{\text{f}\#_1}\right)^2 \frac{t_1}{t_2}$$

Substituting given quantities, we have

$$\frac{160}{25} = \left(\frac{\text{f}\#_2}{5.6}\right)^2 \frac{1/30}{1/30}$$

or

$$160/25 = 2[(\text{f}\#_2)^2/(31.36)]$$

or

$$(\text{f}\#_2)^2 = [(31.36)(160)]/50 = 100$$

and

$$\text{f}\#_2 = 10$$

The closest f number on the camera being used is f/11; therefore, this setting is used.

EXPERIMENT C-2. Using a Camera

In this experiment you will use the relationship among f number, film speed, and exposure time to predict settings for a camera. Take out the work sheets at the end of this module. Complete these sheets as you do the experiment.

1. Set up the pinhole camera as you used it in Experiment A-1. Use the 1 mm pinhole and the same distance of front plate to camera back as in Experiment A-1, and place the optical bench in approximately the same position. Load the camera with Polaroid type 108 color film. Look at your data from Experiment A-1.

   What was your best exposure time for the 1 mm pinhole when you used the black and white film?

2. For a pinhole camera, exposure time and film speed are related by the equation

   $$Z_2/Z_1 = t_1/t_2$$

   The speed of the black and white film is 3000. The speed of the color film is 75.

   From the film speeds and the exposure time with the black and white film, calculate the exposure time you should use for the color film.

3. Make an exposure using the time interval determined in Step 2. Develop the film for exactly 1 minute.

   How does this exposure compare with the black and white exposure from Experiment A-1?

   Adjust the exposure time, if necessary, to give a good exposure.

4. Calculate the f number by using the distance from the pinhole and front plate to the camera back and the diameter of the aperture.

5. Replace the pinhole with the lens and 5 mm aperture.

   Calculate the f number for the lens and aperture.

6. You know the correct f number and the exposure time for *black and white* 3000 speed film for a pinhole camera. Use that data plus the f number of your lens and aperture size to determine the exposure time for 75 speed color film. For this calculation, you will need Equation (12).

7. How does this picture compare with the pinhole color picture?

   You should use the rest of your film to verify calculated exposure times for other apertures.

SUMMARY OF SECTION C

The following statements are intended to summarize the concepts, definitions, and principles you have learned in this section of the module.

The relationship of image position to object position and focal length, $xx' = f^2$, and the relationship between lateral magnification and the ratio of focal length to object distance, $H_i/H_o = f/x$, both can be derived from the properties of a converging lens.

When an object is placed between a converging lens and its focal point, the lens becomes a magnifying glass, and the image is virtual and upright.

For a compound lens the focal length cannot be found simply from measuring the distance from a focal point to the "lens." For a compound lens the focal length is given either by $\sqrt{xx'}$, or by the expression $f = H_i/\alpha$, where α is the angle subtended (in radians) at the lens by a distant object.

The brightness of an image produced by a camera lens is proportional to the area of the lens opening. This brightness is therefore proportional to the square of the lens diameter. In symbols, these relationships are

$$B \propto A_{\text{lens}}$$

$$B \propto D^2{}_{\text{lens}}$$

The brightness of an image produced by a camera lens is inversely proportional to the square of the image height. In symbols,

$$B \propto 1/H_i{}^2$$

The height of an image of a distant object produced by a camera lens is proportional to the focal length of the lens. The proportionality constant is the angle (in radians) subtended by the object at the lens. In symbols,

$$H_i = \alpha f$$

The total amount of light entering a camera lens aperture is proportional to the time the aperture is open and to the square of the ratio of aperture diameter to lens focal length. In symbols, this relationship is

$$(\text{amount of light}) \propto (d/f)^2\, t$$

The ratio of the focal length of a lens to the diameter of the aperture admitting light through the lens is called the f number. In symbols,

$$\text{f\#} = f/d$$

For a given type of film in a camera, correct exposure times and f numbers must obey the relation,

$$t_2/t_1 = (\text{f\#}_2/\text{f\#}_1)^2$$

if the initial time and f number give a correct exposure.

For correct exposure of film, the relationship among film speed, Z, f number, and exposure time is given by

$$\frac{Z_2}{Z_1} = \left(\frac{\text{f\#}_2}{\text{f\#}_1}\right)^2 \frac{t_1}{t_2}$$

if the initial film speed, exposure time, and f number give a correct exposure.

SUMMARY OF THE MODULE

You have learned much about cameras and optics in this module.

You now understand the reasons why Equations (1) and (2) work for thin lenses. You also understand how both real and virtual images can be produced, and that real images really have the light rays passing through them while virtual images do not.

You should be able to find the focal points and focal lengths of either thick or thin lenses. For either kind of lens, you should be able to calculate the positions and sizes of images using Equations (1) and (2). For any kind of lens, the image height of an object is proportional to the focal length f.

The brightness of an image depends on the ratio of focal length to lens diameter, called f number. The brightness is also inversely proportional to the square of the f number.

In this module, we have not examined the chemistry of film exposure and development, certain aberrations (e.g., *coma*), depth or field, or field of view.

COMPUTATION SHEET

EXPERIMENT A-1
Work Sheets

Name____________________________

1. diameter = .25 mm
exposure time = ____________s

____

____

____

2. diameter = .50 mm
exposure time = ____________s

____

____

____

3. diameter = 1.0 mm
exposure time = ____________s

4. ____________________________

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5. ____________________________

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6. ____________________________

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7. exposure time = ____________s

8. ____________________________

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9. ____________________________

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10. ____________________________

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11. ____________________________

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12. ____________________________

13. ____________________________

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14. ____________________________

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15. ____________________________

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16. ____________________________

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17. ____________________

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18. ____________________

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19. ____________________

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20. ____________________

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21. ____________________

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22. ____________________

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COMPUTATION SHEET

EXPERIMENT A-2
Work Sheets

Name______________________________

1. Thin lens:__________________________

   Achromatic lens:____________________

2. ______________________________

3. ______________________________

4. ______________________________

5. ______________________________

6. __________cm

7. __________cm

8. ______________________________

9. ______________________________

10. ______________________________

11. ______________________________

12. ______________________________

COMPUTATION SHEET

EXPERIMENT B-1
Work Sheets

Name____________________________

1. ____________________________

2. ____________________________

3. Lens A $f=$ ________________
   Lens B $f=$ ________________
   Lens C $f=$ ________________

4.

	Lens A		Lens B		Lens C	
Trial	x	x'	x	x'	x	x'
1						
2						
3						
4						
5						

5. ____________________________

6. ____________________________

7. ____________________________

8. ____________________________

9. Lens B: Slope = ____________
   Lens C: Slope = ____________

10. ____________________________

11. ____________________________

12. ____________________________

13. ____________________________

14. ____________________________

15.

Trial	H_o	H_i	x	x'
1			5 cm	
2			10 cm	
3			15 cm	
4			20 cm	
5			25 cm	

16. ____________________________

17. ____________________________

18. ______________________________
____
____

19. ______________________________
____
____
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COMPUTATION SHEET

EXPERIMENT C-1
Work Sheets

Name______________________________

1. Position of one focal point____________
   Distance from the focal point to the center of the lens_______________

2. Position of the other focal point _______________
   Distance from the focal point to the center of the lens_______________

3. $x =$ ____________
   $H_o =$ ____________

4. $x' =$ ____________
   $H_i =$ ____________

5. $f =$ ____________

6. $H_i/H_o =$ ____________

____

____

____

____

____

____

7. $f =$ ____________

COMPUTATION SHEET

EXPERIMENT C-2
Work Sheets

Name______________________________

1. Black and white exposure time:
   ________________s

2. Color exposure time:
   ________________s

3. ____________________________________
   ____
   ____
   ____

4. Pinhole f number________________

5. Lens f number________________

6. Calculated exposure time:
   ________________s

7. ____________________________________
   ____
   ____
   ____

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